On the Performance of Probabilistic Flooding in Wireless Mobile Ad Hoc Networks

A Thesis Submitted

By

Muneer O. Bani Yassein

For

The Degree of Doctor of Philosophy

To

The Faculty of Information and Mathematical Sciences
University of Glasgow

© Muneer Bani Yassein, December 2006.

Abstract

Broadcasting in Mobile Ad hoc Networks (MANETs) is a fundamental data dissemination mechanism, with important applications, including route query in many routing protocols, address resolution and any scenario requiring the diffusing of information (alarm signals for example) across the whole network. Broadcasting in MANETs has traditionally been based on flooding, but this can induce broadcast storms that severely degrade network performance due to redundant retransmission, collision and contention.

Probabilistic flooding, where a node rebroadcasts a newly arrived one-to-all packet with some probability, *p*, was an early suggestion to reduce the broadcast storm problem. However, to date, there has been no attempt to analyse in depth the performance behaviour of such an approach in a MANET environment. The first part of this thesis investigates the effects on the performance of probabilistic flooding of a number of important MANET parameters, including node speed, traffic load and node density. It transpires that these parameters have a critical impact both on reachability and on the number of so-called "saved rebroadcast packets" achieved. For instance, across a range of rebroadcast probability values, as network density increases from 25 to 100 nodes, reachability achieved by probabilistic

flooding increases from 85% to 100%. Moreover, as node speed increases from 2 to 20 m/sec, reachability increases from 90% to 100%.

Our study has also revealed that conventional probabilistic flooding frequently does not achieve a high degree of reachability partly because each node in the network has the same probability of rebroadcasting regardless of the number of neighbours. When a node is in a sparse region of the network, re-broadcasting is relatively more important while the potential redundancy of rebroadcast is low because there are few neighbours which might rebroadcast the packet unnecessarily. Further, in such a situation, contention over the wireless medium resulting from spurious broadcasts is not as serious as in scenarios with medium or high density node populations. This thesis argues that the probability of a node in a sparse region to re-broadcast should be set higher than for nodes situated in denser regions. Extensive simulation experiments have been performed in order to determine the minimum, average and maximum number of neighbours for MANET network nodes subject to a wide range of scenarios. It is argued here that such information can be exploited to estimate better the rebroadcast probability for any given node. To illustrate this, the second part of this thesis proposes two new probabilistic algorithms that dynamically adjust the rebroadcasting probability contingent on node distribution using only one-hop neighbourhood information, without requiring any assistance of distance measurements or location-determination devices. The performance of the new algorithms is assessed and compared to blind flooding as well as the fixed probabilistic approach. It is demonstrated that the new algorithms have superior performance characteristics in terms of both reachability and saved rebroadcasts. For instance, the suggested algorithms can improve saved rebroadcasts by up to 70% and 47% compared to blind and fixed probabilistic flooding, respectively, even under conditions of

high node mobility and high network density without degrading reachability.

To date there has been comparatively little activity with regard to investigating the performance merits of probabilistic flooding in real applications. Addressing this gap, the final part of the thesis assesses the impact of probabilistic flooding on the performance of routing protocols in MANETs. To this end, our newly proposed algorithms as well as fixed probabilistic flooding are incorporated in the Ad hoc On-Demand Distance Vector (AODV) routing protocol; one of the well-known and widely studied algorithm over the past few years. Our performance results indicate that using our new probabilistic flooding algorithms during route discovery enables AODV to achieve a higher delivery ratio of data packets while keeping a lower routing overhead compared to using blind and fixed probabilistic flooding. For instance, the packet delivery ratio using our algorithm is improved by up to 19% and 12% compared to using blind and fixed probabilistic flooding, respectively. This performance advantage is achieved with a routing overhead that is lower by up to 28% and 19% than in fixed probabilistic and blind flooding, respectively.

To my parents, my wife, my children, and my family
for their love, support and encouragement.

Muneer

Acknowledgements

I would like to express my sincere appreciation to my supervisors: Dr. M. Ould-Khaoua and Dr. L.M. Mackenzie. Their continued support and encouragement have always been very valuable, and their constructive suggestions and insightful comments have enabled me to progress in this research work.

I want to extend my thanks to A. Y. Al-Dubai for his useful advice at the start of my Ph.D. program. I would like to thank my officemate, S. Papanastasiou, for his valuable comments and advice. My deepest thanks are also due to my student colleagues: S. Wahab, S. Bani-Mohammad and S. Manaseer. I must extend my gratitude to all the staff of the Department of Computing Science, University of Glasgow, for their kind and friendly support.

I am highly indebted to Jordan University of Science and Technology (JUST), Irbid, Jordan, in particular for their financial support during the course of this research. I am also very grateful due to the staff of the Faculty of Computer and Information Technology, Jordan University of Science and Technology (JUST), Irbid, Jordan, for their great and continuous support.

Finally, I must thank my parents, family, wife, lovely children: Laith, Basel, Osama and Lana, for their unlimited patience and moral support during the course of this research. Without their continuous encouragement and tolerance this work would not be finished.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

One of the early deployments of wireless networks took place in the 1970s and the trend has been growing ever since. During the last decade research interest in the area has grown substantially due to the wide availability and rapid deployment of wireless transceivers in a variety of computing devices such as PDAs, laptop and desktop computers [2, 3, 55]. Initially, the deployment of these wireless technological advances came in the form of an extension to the fixed LAN infrastructure model as detailed in the 802.11 standard [37, 67, 81].

Wireless networks can be classified into two categories [2, 3, 55]. The first category and the most common today, is a wireless network built on-top of a wired network, which creates a reliable infrastructure wireless network [2, 3, 55]. The wireless nodes are also connected to a wired network, and are able to act as bridges in a network of this kind. They are usually called base-stations or access points. An example of this is the cellular-phone network where a phone connects to the base-station. When the phone moves out of range of a base-station it does a hand-off and switches to a new base station within reach. The hand-off should be fast enough to be seamless for the network users. Other more recent networks of this type are Wireless Local Area Networks (WLANs) where transmissions are typically in the 2.4 GHz or 5 GHz frequency bands, and do not require line-of-sight between sender and receiver. Wireless base stations (access points) are often wired to an Ethernet LAN and transmit a radio frequency over an area of several hundred feet through walls and other non-metal barriers. Roaming users can be handed-off from one access point to another as in a cellular phone system [2, 3, 7, 60, 69, 80].

The second category is *Mobile Ad hoc Networks* (or MANETs for short) [2, 3, 23, 55, 67, 68], which are formed by wireless devices that communicate without necessarily using a pre-existing network infrastructure such as that provided by access points. In such networks, each mobile node operates not only as a host where applications can reside, but also as a router so that it can send and receive packets as well as forward packets for other nodes in the network. MANETs are also called *multi-hop packet radio networks* [2, 3, 55, 71, 101] compared to the one-hop station-based cellular networks. The self-configuring nature of MANETs makes them suitable for a wide variety of applications [2, 3, 69]. One of the applications of these networks is communication within groups of people with laptops and other hand-held devices. This type of communication paradigm stimulates the desire for sharing information among mobile devices. Furthermore, MANETs could be useful to deploy in areas such as disaster sites, battlefields, temporary conference meetings, uninhabited field searching. In such environments, where there is often little or no communication infrastructure or the existing infrastructure is inconvenient to use, wireless mobile users could communicate through the rapid formation of a MANET [2, 3, 55].

The communication capabilities of the mobile nodes in MANETs are bounded by their wireless transmission ranges; that is, two nodes can communicate directly with each other only if they are within their transmission ranges. When two nodes are out of one another's transmission range, their communication needs the support of some intermediate nodes which set up a communication between each other to relay packets between the source and destination. For example, in the network shown in Figure 1.1, suppose node C is outside the range of node A's transmission range (the circle in dashed-line around node A) and this node is outside the range of node C's transmission range, therefore, they cannot communicate directly. If A and C wish to exchange a packet, node B has to forward the packet for them, since B is inside both A's and C's transmission ranges.

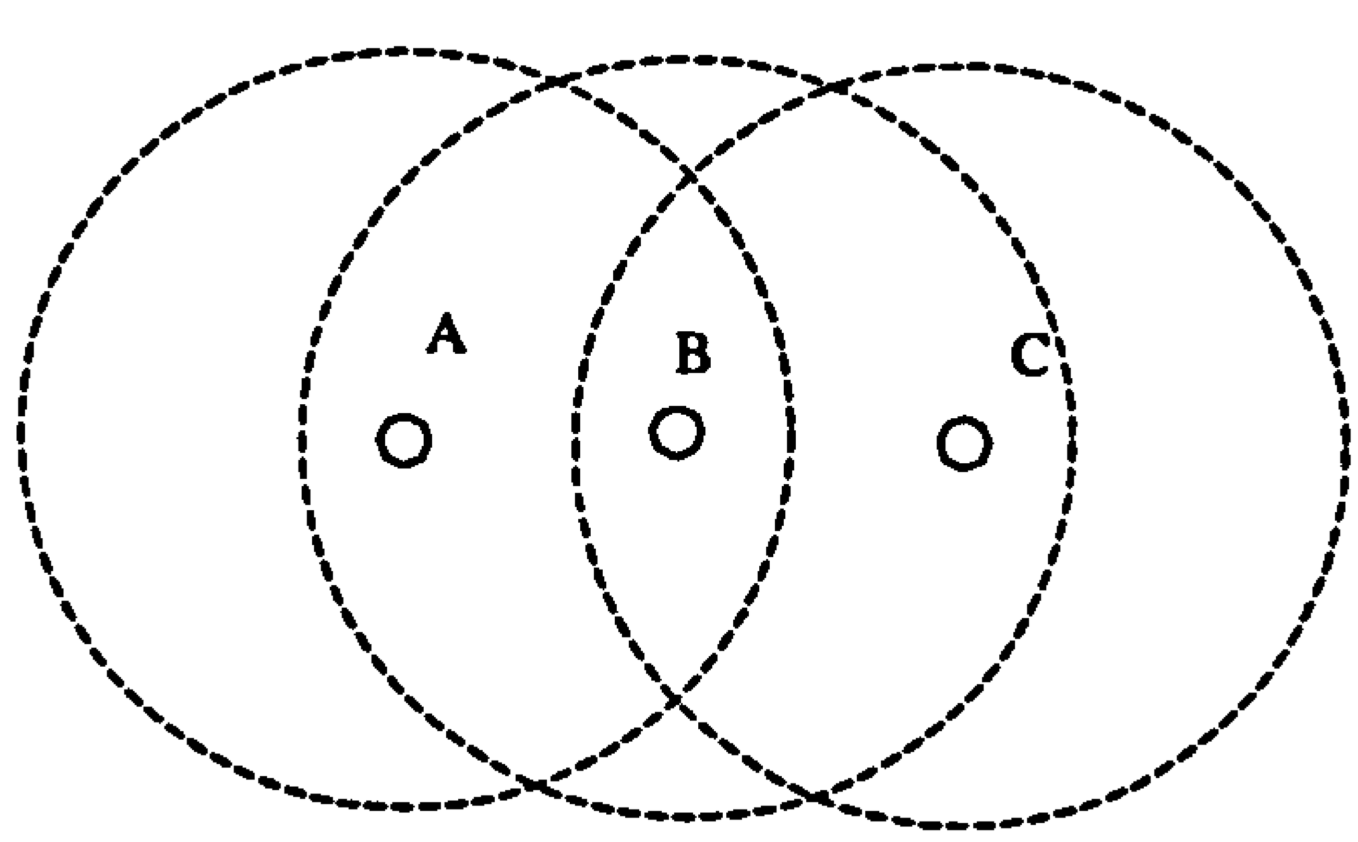

Figure 1.1: A sample mobile ad hoc network (MANET).

1.1 Features of MANETs

MANETs share many of the properties of wired-infrastructure LANs but also possesses certain unique features which derive from the nature of the wireless medium and the distributed function of the medium access mechanism that they employ [2, 3, 79, 80, 102]. These features may be described in turn as considerations stemming from the mobile node, the dynamic network topology and the routing protocol used to establish and maintain communication paths. These characteristics affect the functionality of mechanisms throughout the communication protocol [2, 3, 79, 80, 102].

Independent Nodes: In a MANET, each mobile node is independent of the others, and may function as a host that generates and consumes packets and also as a router that relays packets along network paths.

Dynamic Network Topology: The nodes in the network dynamically establish routing among themselves as they move about, forming their own network connectivity on the fly. Furthermore, since the nodes are mobile, the network topology may change rapidly and unpredictably and the connectivity among the nodes may vary with time.

Distributed Operation: The nodes involved in a MANET should collaborate among themselves and each node should act as a relay as needed to implement important functions such as routing and security. Since there is no background network for the central control of the network operations, the control and management of the network must be distributed among the nodes.

Limited Resource: The nodes in a MANET suffer constrained resources compared to their wired counterparts [2, 3, 68]. These constrained resources include the bandwidth capacity of the wireless links which is significantly lower than that of the wired links. Moreover, mobile devices rely on batteries for their energy [26, 61, 72, 73, 83, 95]. One of the most important system design goals is the optimisation of energy conservation.

1.2 Applications of MANETs

MANETs, due to their quick and economically less demanding deployment, find application in several areas. Some of these include: emergency operations, military applications, collaborative and group communication [2, 3].

Emergency Operations: MANETs are very useful in emergency operations such as in environments where the conventional infrastructure-based communication facilities are destroyed due to natural calamities such as earthquakes. Immediate deployment of ad hoc wireless networks would be a good solution for activity coordination. Moreover, the major factors that favour MANETs for such tasks are the self-configuration of the system with minimal overhead, independent of fixed or centralized infrastructure, the freedom and flexibility of mobility, and the unavailability of conventional communication infrastructure.

Military Applications: MANETs can be very useful in setting up a fixed infrastructure for communication among a group of soldiers in enemy territories or inhospitable terrains. Also, they are useful for establishing communication among a group of soldiers for tactical operations. In such environments, MANETs can provide the required communication mechanism very rapidly.

Collaborative and group communication: MANETs can be very useful in setting up the requirement of a temporary communication infrastructure for quick communication with minimal configuration among a group of people in a conference or gathering. For example, consider a group of researchers who want to share their research findings or presentation materials during a conference or a lecture, distributing notes to the class on the fly. In such a case, the formation of a MANET can serve the purpose [69, 81]. Furthermore, group communication is one of the most promising applications for MANETs. For instance, the authors in the framework of the Mobile group communication Project [69] are investigating the viability of developing such type of applications in MANETs. They have developed a Whiteboard application (WB), which implements a distributed whiteboard among users. Each user runs a WB instance on his/her device, selects a topic he/she wants to join, and starts drawing on the canvas. Drawings are distributed to all nodes, and rendered on each canvas.

1.3 Routing Principles in MANETs

The basic routing problem is that of finding an ordered series of intermediate nodes that can transport a packet across a network from its source to its destination by forwarding the packet along this series of intermediate nodes. In traditional hop-by-hop solutions to the routing problem, each node in the network maintains a routing table: for each known destination, the routing table lists the next node to which a packet for that destination should be sent. There are two main routing approaches in MANETs as expressed in IETF recommendations through the RFC process, namely the *proactive* and *reactive* routing concept [51].

1.3.1 Proactive Routing

In proactive routing, each node maintains routes to all reachable destinations at all times. The routing information is usually kept in a table. These tables are periodically updated if the network topology changes. The differences between the different routing protocols are in the way the routing information is updated, detected and the type of information data kept at each routing table. Furthermore, each routing protocol may maintain different number of tables. Optimised Link State Routing (OLSR) [41], Destination-Sequenced Distance Vector (DSDV) [57] are examples of proactive protocols.

1.3.2 Reactive Routing

In this type of routing, only needed routes are explored and maintained. In contrast to table-driven routing protocols all up-to-date routes are not maintained at every node, instead the routes are created as and when required. When a source wants to send to a destination, it invokes the route discovery mechanism to find a path to the destination. The route remains valid till the destination is reachable or until the route is no longer needed. The existing reactive protocols differ in the ways the route discovery and route maintenance are conducted. Ad hoc On-Demand Distance Vector Routing (AODV) [36, 56], Dynamic Source Routing Protocol (DSR) [54], and Temporally Ordered Routing Algorithm (TORA) [35] are examples of reactive protocols.

1.4 Broadcasting in MANETs

Broadcasting is a fundamental operation in MANETs whereby a source node sends the same packet to all the nodes in the network. In the one-to-all model, a transmission by each node can reach all nodes that are within its transmission radius, while in the one-to-one model, each transmission is directed toward only one neighbour (using narrow beam directional antennas or separate frequencies for each node) [17]. Broadcasting has been studied in the literature mainly for the one-to-all model, and most of this study is devoted to that model. The one-to-many model can also be considered, where fixed or variable angular beam antennas can be used to reach several neighbours at once [14].

1.4.1 Applications of Broadcasting

Broadcasting has many important uses and several MANET protocols assume the availability of an underlying broadcast service [7, 12]. Applications which make use of broadcasting include paging a particular node or diffuse information to the whole network (alarm signal for example). It can also be used for route discovery in reactive protocols. For instance, in Ad Hoc On-demand Distance Vector Routing (AODV) [36, 56], Dynamic Source Routing (DSR) [43, 44, 54], a route request is broadcasted in the network to discover a path to a particular destination. Each node keeps the broadcast *ID* and the name of the node from which the packet has been received. When the destination is reached, it replies with a unicast (point-to-point) packet and then each intermediate node is capable of establishing the return routes [36, 43, 44, 54, 56].

Any communication protocol for MANETs should contend with the issue of interference in the wireless medium. When two or more nodes transmit a packet to a common neighbour at the same time, the common node will not receive any of these packets. In such a case, we say that a collision has occurred at the common node. In multi-hop MANETs where all the nodes may not be within the transmission range of the source, intermediate nodes may need to assist in the broadcast operation by retransmitting the packet to other remote nodes in the network. Retransmissions use up valuable resources in the network such as power and bandwidth. Hence, it is important to choose the intermediate nodes carefully so as to avoid redundancy in retransmissions.

1.4.2 Characteristics of Broadcasting

We consider a MANET consisting of a set of cooperating mobile nodes. Each mobile node is equipped with a CSMA/CA (carrier sense multiple access with collision avoidance) transceiver which can access the air medium following the IEEE 802.11 protocol [37, 67, 81].

The broadcasting is spontaneous; any mobile node can issue a broadcast operation at any time. The broadcasting is unreliable in that a broadcast is transmitted via a CSMA/CA manner, and no acknowledging mechanism is used. Note that in IEEE 802.11 [9, 37, 67, 81] the MAC specification does not allow acknowledging on receiving a broadcast transmission. This is reasonable because, if all receiving nodes send acknowledgments to the sending node, these acknowledgments are likely to collide with each other at the sender's side, resulting in the "many-to-one" broadcast storm [10, 14, 18, 40]. After receiving a broadcast packet, a node may rebroadcast the packet at most once. In addition, it is assumed here that a node can detect duplicate broadcast packets. This is essential to prevent endless flooding of the packet. One way to do so is to associate with each broadcast packet a tuple (source *ID*, sequence number).

A broadcast request can be issued by any source node which has a packet to be distributed to the whole network. This broadcast packet is propagated in the network to reach all the nodes with a minimal number of re-transmission. All other nodes have a responsibility to help in propagating the packet by re-broadcasting it. An attempt should be made to successfully distribute the packet to as many nodes as possible without incurring substantial computational and communication overhead.

CBR traffic is usually used for connections that transport traffic at a fixed bit rate, where there is natural dependence on time synchronization between the traffic source and destination. CBR is often adopted for any type of data for which end-systems require a predictable response time and amount of bandwidth. In this research, we have used CBR traffic for evaluating the broadcast algorithms discussed so that a regular amount of data is injected into the network to ensure that any kind of change in the saved broadcast and reachability metrics is a result of the broadcast algorithm in use and not affected by the status of the traffic sources. Moreover, we could not examine any other type of traffic, VBR or Poisson, due to mainly to time constraints.

1.5 Performance Metrics

The performance of broadcast protocols can be measured by a variety of metrics [10, 14, 18, 25, 40]. A commonly used metric is the number of re-transmissions or alternatively, saved rebroadcasts, a complementary measure, can be used when comparing the relative performance of different protocols [10, 14, 18, 25, 40]. Another important metric is reachability, or the percentage of mobile nodes receiving the broadcast packet over the total number of mobile nodes that are reachable, directly or indirectly [10, 14, 18, 25, 40]. It is worth noting that time delay or latency is sometimes used, which is the time needed for the last node in the network to receive the broadcast initiated at a given source [10, 18].

1.6 Related work

One of the earliest broadcast mechanisms proposed in the literature is *flooding* [10, 14, 28, 36, 85], where each node receiving a broadcast packet simply re-transmits it to all its neighbours. The only optimisation that could be applied to this approach is that nodes remember packets received during the flooding operation, and do not act if they receive repeated copies of the same packet [42, 85]. However, a straightforward broadcasting by flooding is usually costly and results in serious transmission redundancy and collisions in the network; such a scenario has often been referred to as the broadcast storm problem [10, 14, 18, 40] and has generated many challenging research issues [10, 14, 18, 40]. A number of researchers [10, 14, 17, 18, 40] have identified this problem by showing how serious it is through simulations and analyses. They have proposed several schemes to reduce redundant rebroadcasts and differentiate timing of rebroadcasts to alleviate this problem.

Williams and Camp [17] have classified the broadcast protocols into *flooding*, *probability-based*, *counter-based*, *distance-based*, *location-based* and *neighbour knowledge* schemes. Similarly, neighbour knowledge schemes can be divided into *selecting forwarding neighbours* and *clustering-based*.

In the probabilistic scheme, when receiving a broadcast packet for the first time, a node rebroadcasts the packet with a probability *p*; when *p*=1, this scheme reduces to blind flooding. The counter-based scheme inhibits the rebroadcast if the packet has already been received for more than a given number of times. In the distance-based scheme a node rebroadcasts the packet only if the distance between the sender and the receiver is larger than a given threshold. In the location-based scheme, a node rebroadcasts a packet only when the additional coverage due to the new emission is larger than a certain bound. In the selecting forwarding neighbours a broadcasting node selects some of its 1-hop neighbours as rebroadcasting nodes. Finally, the cluster structure is a simple backbone infrastructure whereby the network is partitioned into a group of clusters. Each cluster has one cluster head that dominates all other members in the cluster. A node is called a gateway if it lies within the transmission range of two or more cluster heads. Gateway nodes are generally used for routing between clusters. The rebroadcast is performed by cluster heads and gateways. However, the overhead of cluster formation and maintenance cannot be ignored [4, 6, 15, 30].

Broadcast algorithms could also be classified into two main categories: *deterministic* and *probabilistic*. In the first category, algorithms could be further divided into *reactive* schemes and *proactive* schemes. In proactive schemes [4, 6, 11, 19, 21, 22, 82, 90], a broadcasting node selects some of its 1-hop neighbours as rebroadcasting nodes. When a node receives a broadcast packet, it drops the packet if it is not designated as a rebroadcasting node; otherwise, it recursively chooses some of its 1-hop neighbours as rebroadcasting nodes and then forwards the broadcast packet to them. In reactive schemes [1, 16, 24, 27, 31, 75, 77, 82, 88, 89, 94], each node determines by itself whether or not to forward a broadcast packet. In general, these techniques are not sufficiently adaptive to be able to cope with networks with high mobility and node density. This is due to the fact that when the network topology changes frequently, the overhead of discovering and maintaining a model of local network topology (within two or more hops) for each node increases, and may outweigh the benefit of reduction in retransmission [92, 93]. Furthermore, for those proactive techniques, the task of selecting a suitable set of nodes to forward the broadcasts is not trivial and requires significant computation by the mobile nodes. It has been shown in the study of [4, 6, 11, 19, 21, 22, 90] that the determination of minimum connected dominating set is an NP-hard problem.

Probabilistic flooding algorithms are one of the solutions proposed to reduce redundant rebroadcasts in order to alleviate the broadcast storm problem. They are simpler and easier to implement than their deterministic counterparts. However, the authors in [10, 14, 18, 20, 25, 26, 33, 40] have shown that in most cases probabilistic flooding does not achieve high degree of reachability because each node has the same probability to rebroadcast packets regardless of its surrounding, e.g. number of neighbours. The problem derives from the uniformity of the algorithm; every node has the same probability to rebroadcast a given packet. When a node has few neighbours (a *sparse* node), re-broadcasting a packet is relatively more important for two reasons. First, the redundancy of its rebroadcast is lower because the node has fewer neighbours which might rebroadcast the packet unnecessarily. In such a case, collisions resulting from spurious broadcasts are not as serious as in scenarios with medium or high density node populations. Second, the node might be placed in a critical location in that failure to rebroadcast the packet might result in network partitioning [14, 25]. Hence, the probability of such nodes to re-broadcast should be higher than nodes situated in denser topologies.

Tseng *et al* [14] have studied a simple probabilistic flooding scheme. They have shown that the scheme has poor reachability and cannot achieve high level of saved rebroadcast packets, especially in topologies with a low density, because every node has the same probability to rebroadcast the packet, regardless of its number of neighbours. Cartigny and Simplot [25] have suggested a probabilistic scheme where the probability p is computed from the local density n (i.e. the number of neighbours) and a fixed value k as an efficiency parameter to achieve reachability of the broadcast. However, the authors in [25] have not discussed how the parameter k is fixed for a particular network setup.

Zhang and Agrawal [33] have suggested dynamic probabilistic algorithm that combines the properties of probabilistic and counter-based methods. The method enables the originator node to adjust the rebroadcast probability based on the number of duplicate packets received within a random delay time where is counter-based schemes show an inverse relationship between the numbers of times a packet is received at a node and the probability of that node being able to reach additional area on a rebroadcast. In [10, 14, 18] the authors have used a fixed threshold C to inhibit redundant rebroadcasts. If a node has already heard the same broadcast packet more than C times, it will not rebroadcast the packet because it is unlikely that the rebroadcast will provide new information to the node's neighbourhood. It was shown in [10, 14, 18] that a threshold C of 3 of 4 can significantly reduce the redundant rebroadcast in a dense network while achieving a reachability better or comparable to that of flooding. A larger threshold C of 6 will provide less savings of redundant rebroadcast and may behave similar to flooding. Increasing the value of C improves reachability, but, once again, efficiency of the broadcast algorithm in terms of control of redundant rebroadcast will suffer.

To resolve the trade-off between reachability and control of redundant rebroadcasts, there is a need for dynamic counter-based scheme in which each individual node can dynamically adjust the counter value using neighborhood information. It has been argued in [10, 14] that the value of a packet counter does not necessarily correspond to the exact number of neighbors of the node, since some of its neighbors may have failed to rebroadcast the packet according to their local rebroadcast probability.

1.7 Motivations

The broadcast operation has extensive applications in MANETs. For example, it is used in the route discovery process in a number of well-known routing protocols [34, 35, 36, 47, 54, 56], such as Route Request (RREQ) and Route Reply (RREP), [35, 36, 54]. In wireless communication, a channel is shared by all users in that when a sender transmits a packet, all nodes within the sender's transmission range can receive this transmission. This is usually referred to as the *promiscuous receive mode* [40]. The advantage is that one packet can be received by all the neighbours. The disadvantage is that it interferes with the other concurrent transmissions, resulting in the *exposed terminal problem* [67]; that is, an outgoing transmission collides with an incoming transmission. This can also result in the *hidden terminal problem*; that is, a node simultaneously receiving packets from two other nodes that are not aware of each other's transmission [67].

As stated above, blind flooding is very simple to implement, but often leads to the broadcast storm problem. One solution to alleviate the deleterious performance effects of this is to provide efficient probabilistic broadcast algorithms that aim to reduce the number of nodes that retransmit the broadcast packet while still guaranteeing that most or all nodes receive the packet. Although probabilistic flooding schemes have been around for a relatively long time, there has not been so far any attempt to analyse their performance behaviour in a MANET environment. Moreover, no study has analysed the performance of probabilistic flooding taking into the effects of a number of important system parameters in MANETs, such as the node speed, pause time, traffic load, and network density.

In most existing probabilistic approaches that have been proposed in the literature [14, 18, 20, 25, 33, 40], the rebroadcast probability at a given node is fixed. This could lead to poor reachability, as discussed in [14]. One of the causes for this stems from the fact that every node in the network has the same probability to rebroadcast a packet, regardless of the number of its neighbouring nodes. In a dense network, multiple nodes could share similar transmission coverage. Thus, randomly having some nodes not re-broadcasting the packet saves the node's as well as network's resources without harming delivery effectiveness. On the other hand, in a sparse network, there is much less shared coverage; thus some nodes might not receive the broadcast packet unless the probability is set high enough. Consequently, the rebroadcast probability should be set differently from one node to another in order to account for a given node's coverage.

Ideally, the rebroadcast probability p should be high in a node located in a sparse region while relatively low in a node located in a dense region. If p is too low reachability might be poor while if p is set too high, many redundant rebroadcasts might be generated. In order to achieve both high saved broadcast and high reachability when network topology changes frequently, the rebroadcast probability should be set high for the nodes located in sparse areas and low for the nodes located in dense areas. This research work suggests and investigates the performance of new probabilistic flooding algorithms where the rebroadcast probability at a node is dynamically adjusted as per the node coverage distribution and movement using one-hop neighbourhood information to increase reachability and saved rebroadcast.

1.8 Main Contributions

Existing studies [10, 14, 18, 25] have revealed that probabilistic flooding incurs a lower overhead compared to blind flooding, while maintaining a sufficient degree of propagation for broadcast packets. However, these studies have not taken into consideration the impact of important factors in a MANET including node mobility, network density, and injected traffic load to assess the performance of probabilistic flooding. In an effort to gain a deep understanding of the performance behaviour of probabilistic flooding in MANETs, the first part of this research work investigates the effects of node speed, network density, traffic load on two metrics, notably reachability and saved rebroadcasts, when nodes moves according to the popular random waypoint model [51]. To the best of our knowledge, this is the first study to conduct such a performance analysis of probabilistic flooding in a MANET environment [66, 104].

In most existing probabilistic algorithms [10, 14, 20, 25] every node has the same probability to rebroadcast a packet, regardless of its number of neighbours. It would be very desirable to devise a flooding scheme that takes into account the current node's coverage when deciding to re-broadcast a packet. Hence, nodes situated in a sparse region should have the probability of re-broadcast set higher than in nodes situated in a dense region. Towards this end, the second part of this research analyses extensively the topological characteristics of a MANET when nodes move according to the widely adopted random way point mobility model [51]. Numerous ns-2 simulation experiments are performed in order to determine the minimum, average and maximum number of neighbours for a given node in the network for a wide range of scenarios. Such topological information is used to set the broadcasting probability at a given network node.

The third part of this thesis proposes two new probabilistic flooding algorithms that dynamically adjust the rebroadcasting probability as per the node's neighbourhood distribution over one hops neighbourhood. This is done based on locally available information and without requiring any assistance of distance measurements or exact location determination devices. In the first proposed algorithm, referred to as the adjusted probabilistic flooding, only information on one-hop neighbours is required. Short 'Hello' packets, containing the *ID* of the senders only, are used to collect such information. Furthermore, the new algorithm does not require a positioning system, because a node compares the neighbour lists to deduce probabilistic information. In the new algorithm, the rebroadcast probability in nodes located in sparse regions is set higher than those located in dense regions.

The second new algorithm referred to as the highly adjusted probabilistic flooding, is a further refinement over our first proposed algorithm. While in the first algorithm the network regions are divided into sparse and dense, in our second algorithm the regions are divided into sparse, medium, and dense. The rebroadcast probability in the nodes located in the three regions is set accordingly to reflect their current surroundings [105].

As stated above, there have been a number of research studies on probabilistic flooding, including ours above. However, there has been so far comparatively a little activity on investigating the performance merits of the probabilistic flooding algorithms in real applications. In an effort towards filling this gap, the final part of this research assesses the impact of probabilistic flooding on the performance of AODV; one of the well-known and widely studied routing protocols over the past a few years. Our newly proposed algorithms as well as fixed probabilistic flooding are incorporated into AODV and compared against the traditional AODV version that employs simple flooding [106]. To the best of our knowledge, this is the first study that analyses the performance of probabilistic flooding outside the context of pure one-to- all broadcast communication.

Thesis Statement:

Broadcasting is a fundamental operation in MANETs and has many important uses and several protocols assume the availability of an underlying broadcast service. Unfortunately, inefficient broadcasting is expensive and may lead to a broadcast storm problem which can dramatically affect network performance. However, the degrading effects of such a problem could be reduced if a probabilistic broadcasting method can be used effectively to decrease the number of rebroadcasts, and as a result reduce the chance of contention and collision among neighbouring nodes.

The goals of this dissertation are derived from the motivations listed in the previous section and are summarised in the following thesis statement

T1: Probabilistic flooding, where a node decides to rebroadcast its packet using a fixed probability p, is one of the earliest suggested approaches to broadcasting in MANETs. However, there has not been so far any attempt to analyse in depth its performance behaviour in a MANET environment. The first part of this thesis investigates using extensive simulations the performance impact of a number of important parameters in MANETs including the node speed, traffic load, and network density. The results reveal that most of these parameters have a great impact on the reachability and saved rebroadcast level achieved in a given MANET.

T2: In order to fix the rebroadcast probability, we have extensively analysed the topological characteristics of a MANET when nodes move according to the widely adopted *random way-point mobility model.* We have used a short 'Hello' interval in order to keep up-to-date neighbourhood information in the dynamic network environment. We have also studied the effects of 'Hello' packets on neighbourhood information when the system parameters, including node speed and node density, are varied.

T3: While most previous studies have used a *fixed* re-broadcasting probability irrespective of the node status, this research proposes two new probabilistic algorithms that dynamically adjust the rebroadcasting probability as per the node's neighbourhood distribution and node movement using one-hop neighbourhood information. The results show that the new algorithms outperform fixed probabilistic flooding in terms of both reachability and saved rebroadcast.

T4: Our newly proposed algorithms as well as fixed probabilistic flooding have been incorporated in the Ad hoc On-Demand Distance Vector (AODV) routing protocol; one of the well-known and widely studied algorithm over the past a few years. The performance results show that AODV with probabilistic-based route discovery outperforms the traditional AODV in terms of reachability, saved rebroadcast, as well as delay and packet delivery ratio.

1.9 Outline of the Thesis

The rest of the thesis is organised as follows.

Chapter 2 provides some preliminaries that are required for understanding the subsequent chapters. The chapter starts with an overview of the broadcast storm problem which causes a serious degradation in network performance due to extreme redundant retransmission, collision and contention. This is then followed by a classification of the existing broadcast algorithms suggested for MANETs.

Chapter 3 analyses the performance probabilistic flooding behaviour in MANETs with various speeds, traffic loads, and network densities.

Chapter 4 provides an analysis of the topological characteristics of MANETs when nodes move according to the random way point mobility model.

Chapter 5 presents the new adjusted probabilistic flooding algorithm where the rebroadcasting probability at the nodes is dynamically adjusted using one-hop neighbourhood information.

Chapter 6 presents the new highly adjusted probabilistic flooding algorithm where the rebroadcasting probability is further refined using one-hop neighbourhood information

Chapter 7 investigates the performance merits of the highly adjusted probabilistic flooding algorithms in real applications. To do so, the newly proposed algorithms as well as fixed probabilistic flooding are incorporated in the existing AODV routing protocol.

Chapter 8 summarises the results presented in this thesis and discusses some possible directions for future research work.

Chapter 2

Preliminaries and Related Works

Wireless mobile networks, including MANETs, have become a favorable subject in academic research areas [2, 3, 49, 53, 76, 78, 95] as well as commercial product development [40, 49, 69, 70, 71, 81, 86]. MANETs are attractive for various purpose applications including conference meetings, electronic classroom, and search-and-rescue operations. The main feature of these networks is that do not need to use fixed gateways for packet routing. Instead, each mobile node can act as a router and maintains routes to other nodes in the network.

Broadcast is one of the most fundamental operations in MANETs. It refers to a process of transmitting a packet from a source to all nodes in a network so that each node receives a copy of the packet. The broadcasting protocol can dramatically affect the performance of a MANET [10, 14, 18, 33]. Proper use of a broadcasting method can reduce the number of rebroadcasts, and as a result reduce the chance of contention and collision among neighboring nodes. The main objective of this chapter is to provide background on broadcast in MANETs as well as review and describe some broadcast algorithms that have been reported in the literature.

The remainder of this chapter is organised as follows. Section 2.1 describes the characteristics of broadcast operations. Section 2.2 provides an overview of the existing broadcast algorithms suggested for MANETs and also describes the operations of some well-known algorithms that are directly relevant for the reminder of this thesis. Section 2.3 includes a description of the random waypoint model. Section 2.4 includes a description of Ad hoc On-Demand Distance Vector (AODV) routing. Section 2.5 lists the assumptions which have been made in this research, and which apply throughout this thesis. Section 2.6 provides a justification on the method of the study. Finally, Section 2.7 summarises this chapter.

2.1 Characteristics of Broadcast Operations

Blind flooding is the simplest approach for broadcasting where every node in the network forwards the packet exactly once. Blind flooding ensures maximal coverage of the entire network. That is, the broadcast packet is most likely to reach every network node.

In this study, we consider a MANET consisting of a set of cooperating mobile nodes. Each mobile node is equipped with a CSMA/CA (carrier sense multiple access with collision avoidance) transceiver which can access the air medium following the IEEE 802.11 protocol [37]. A broadcast request is issued by a source node that has a packet to be distributed to the whole network. The goal is that the broadcast packet is propagated in the network to reach all the nodes with a minimal number of re-transmissions. All other nodes have a responsibility to help in propagating the packet by re-broadcasting it. An attempt should be made to successfully distribute the packet to as many nodes as possible without incurring substantial communication overhead.

The Broadcast Storm Problem:

The broadcast storm problem is a side-effect of simple flooding, and it motivates the development of the existing broadcasting protocols described in the next sections. The simple flooding protocol makes radio signals likely to overlap with others in a geographical area. This is usually very costly and will result in serious drawbacks: redundant rebroadcast, contention, and collision [10, 14, 18, 20]. These drawbacks comprise the broadcast storm problem. We now consider each of the drawbacks in greater detail

Redundant Rebroadcast: This occurs when a node rebroadcasts packets that neighbour nodes have already received [10, 14, 18, 20]. We illustrate the problem using Figure 2.1 notice that edges between nodes mean that nodes are within the range of each other.

1. Node *A* broadcast a packet to *B* and *C*.
2. Node *B* rebroadcast to *A* and *C* which is clearly redundant as both *A* and *C* have a copy of the packet.

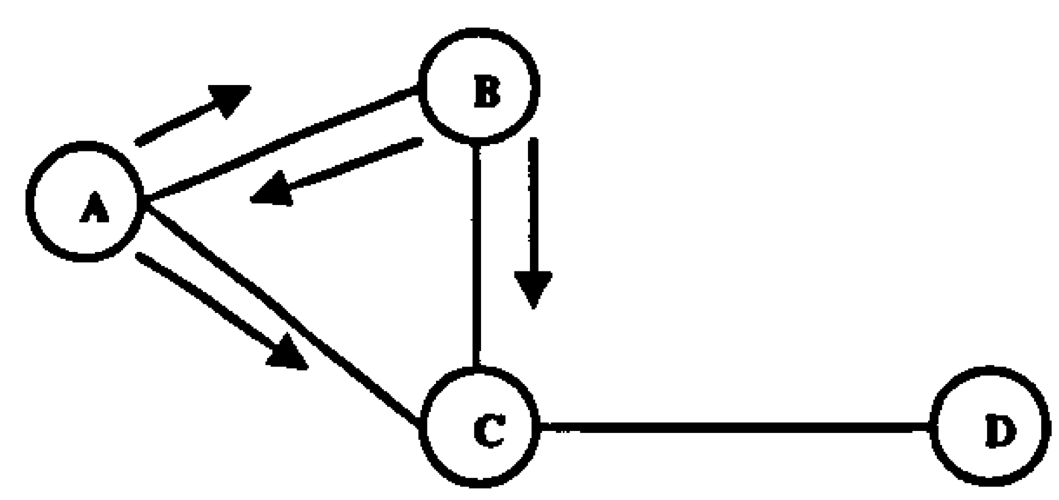

Figure 2.1: Illustration of redundant rebroadcasting and contention

Contention: When neighbours receive a broadcast from a node, they will try to rebroadcast the packet. Since these neighbours are close to each other, there is a risk that they will compete for transmission time. This causes delays in the dissemination of data. We illustrate the problem using Figure 2.1.

1. Node *A* broadcast to *B* and *C*.
2. Both node *B* and node *C* have to rebroadcast the packet.
3. Node *B* is the fastest and sends the packet even though all its neighbours have already received the data.
4. Node *C* wants to send to *D*, but *C* is aware that this is not possible for the moment because the channel is busy. Node *C* has to wait then.

Collision: Neither channel reservation mechanism nor acknowledgment mechanism are used in the link layer when using flooding. This gives a higher chance for simultaneous transmissions causing collisions. But, since reservation and acknowledgments mechanisms can be too expensive in transmission time, flooding based protocols can take advantage in not to using them. When collisions are detected, packets are dropped by the receiver. Since acknowledgment mechanism is not used, the sender never knows that the packet has been dropped. Figure 2.2 shows how collision between two nodes affects a third one.

1. Node *A* broadcasts to *B* and *C*.

2. Both node *B* and *C* rebroadcast the packet immediately.

3. The transmissions from *B* and *C* collide and the packet received by node *D* is dropped.

This collision problem is very serious because the packet never gets forwarded and data is lost.

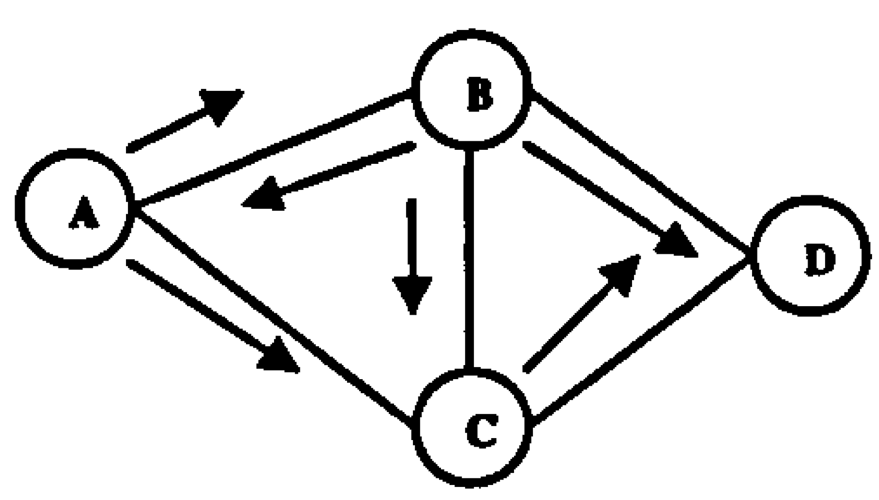

Figure 2.2: Illustration of collision.

Prevention of Infinite Loops: Most existing broadcast algorithms [10, 14, 18] require a node to rebroadcast a given packet not more than one time in order to prevent infinite "transmission" loops. Thus, each broadcast protocol requires that nodes cache the original source node *ID* of the packet and the packet *ID*. This allows the protocol to uniquely identify each broadcast packet.

'Hello' packet: broadcast schemes may require different neighbourhood information, which is reflected in the contents of packets sent by nodes when they move, react to topological changes, change activity status, or simply periodically send update packets [74]. A commonly seen 'Hello' packet may contain, in addition to its own *ID*, its position, one bit for dominating set status (one bit saying to neighbours whether or not node considers itself to be in a specific designated set; e.g. dominating set as discussed in [16, 75, 84, 89, 90, 94]), a list of 1-hop neighbours, and its degree (number of its neighbours). Other contents are also possible, such as a list of 1-hop neighbours with their positions, or a list of 2-hop neighbours, or even global network information; for instance the Global Position System (GPS) can provide geographic location information (if required) to nodes in a wireless network by communicating with a satellite network [100].

Broadcast packet contents: A broadcast packet sent by the source, or retransmitted, normally contains the broadcast packet. In addition, it may contain a variety of information needed for proper functioning of the broadcast protocol, such as the information previously listed for 'Hello' packets, plus a few bits, or a list of forwarding neighbours, informing them whether or not to re-transmit the packet [4, 6, 11, 19, 21, 22, 90].

2.2 Existing Broadcast Algorithms in MANETs

Broadcast operations are frequently performed in a MANET (e.g. to find a route to a particular node or page a particular node). Radio signals are likely to overlap with others in a given geographical area, and a straightforward broadcast by flooding is often expensive and results in the broadcast storm problem [10, 14, 18]. A number of researchers have recognized this problem by showing the serious degradation that it could cause to MANET performance [10, 14, 18]. The studies in [10, 14, 18] have proposed several schemes to reduce redundant rebroadcasts.

Williams and Camp [17] have classified broadcast protocols into: neighbour knowledge-based, location-based, distance based, simple (blind) flooding, counter-based, and probabilistic schemes. Furthermore, the neighbour knowledge schemes are divided into selecting forwarding neighbours and clustering based. In the area based schemes, it is assumed that each node is equipped with a positioning device such as GPS [14, 18, 100]. Hence, such schemes will not form part of this discussion as they limit the scope of any proposed algorithms to GPS enabled agents which are a small subset of the existing MANET enabled wireless agents. The purpose of this section is to review the existing schemes that have been proposed in the literature for broadcasting in MANETs [1, 4, 10, 11, 14, 25, 27, 33, 77, 82, 88, 89, 94]

2.2.1 Neighbour Knowledge-Based Schemes

Neighbour knowledge based schemes [1, 19, 21, 27] maintain a state on their neighbourhood, which is used in the decision to rebroadcast, via 'Hello' packets. The goal of the added cost is to reduce the number of redundant transmissions. These schemes are divided into selecting forwarding-neighbours [1, 21] and clustering-based schemes [19].

2.2.1.1 Selecting Forwarding Neighbours Algorithms

The selecting forwarding-neighbours algorithms as discussed in the literature include flooding with self pruning [85], scalable broadcast [1], dominant pruning and multipoint relaying [21, 82]. These are discussed below.

Flooding with Self Pruning Algorithm [85]:

The simplest version of the neighbour knowledge-based schemes is what Lim and Kim refer to as flooding with self pruning [85]. This protocol requires that each node have knowledge of its 1-hop neighbours which is obtained via periodic 'Hello' packets. A node includes its list of known neighbours in the header of each broadcast packet. A node receiving a broadcast packet compares its neighbour list to the sender's neighbour list. If the receiving node would not reach any additional nodes, it refrains from rebroadcasting; otherwise the node rebroadcasts the packet.

Scalable Broadcast Algorithm (SBA) [1]:

This algorithm requires that all nodes have knowledge of their neighbours within a two hop radius [1]. This neighbour knowledge coupled with the identity of the node from which a packet is received allows a receiving node to determine if it would reach additional nodes by performing a rebroadcast. The 2-hop neighbour knowledge is achievable via periodic 'Hello' packets; each 'Hello' packet contains the node's identifier (e.g., *IP* address) and the list of known neighbours. After a node receives a 'Hello' packet from all its neighbours, it has 2-hop topology information centred at itself.

Dominant Pruning Algorithm [82]:

Dominant pruning also uses 2-hop neighbour knowledge, obtained via 'Hello' packets, for routing decisions [82]. Unlike SBA [1], however, dominant pruning requires the rebroadcast nodes to proactively choose some or all of its 1-hop neighbours as subsequent rebroadcast nodes. Only those selected nodes are allowed to rebroadcast. Nodes inform their neighbours to rebroadcast by including their address as part of a list in each broadcast packet header. When a node receives a broadcast packet it checks the header to see if its address is part of the list. If so, it uses a greedy set cover algorithm to determine which subset of neighbours should rebroadcast the packet, given knowledge of which neighbours have already been covered by the sender's broadcast. The greedy set cover algorithm, as adapted in [82], recursively chooses 1-hop neighbours which cover most of the 2-hop neighbours and recalculates the cover set until all 2-hop neighbours are covered.

Multipoint Relaying Algorithm [21]:

Multipoint relaying [21] is similar to dominant pruning [82] in that upstream senders explicitly choose the rebroadcast nodes. For instance, say node *X* is originating a broadcast packet it has previously selected some, or in certain cases all, of it one hop neighbours to rebroadcast all packets they receive from node *X*. The chosen nodes are called Multipoint Relays (MPRs) and they are the only nodes that are allowed to rebroadcast the packet received from node *X*. Each MPR is required to choose subset of its 1-hop neighbours to act as MPRs as well. Since a node knows the network topology within a 2-hop radius, it can select 1-hop neighbours as MPRs that most efficiently reach all nodes within the 2-hop neighbourhood.

The multi-point relaying method, discussed in detail by Qayyum, Viennot and Laouiti [21], the dominant pruning method proposed by Lim and Kim [82], and SBA proposed by Peng and Lu [1] are based on a heuristic which selects a minimal size subset of neighbours of a given node *X* that can 'cover' all 2-hop neighbours of *X*. A node is called 'covered' if it received (directly or via re-transmissions by other nodes) the packet originating at *X*. Relay points of *X* are 1-hop neighbours of *X* that cover all 2-hop neighbours of *X* That is, after all relay points of *X* re-transmit the packet; all 2-hop neighbours of *X* will receive it. The goal is to minimize the number of relay points of *X*. The computation of a multipoint relay set with minimal size is NP-complete problem, as has been proven in [1, 21, 82].

Most existing algorithms in this category can be further divided into reactive and proactive schemes. In proactive schemes [4, 6, 11, 19, 21, 22, 82, 90], a broadcasting node selects some of its 1-hop neighbours as rebroadcasting nodes. When a node receives a broadcast, it drops off the packet if it is not designated as a rebroadcasting node; otherwise, it recursively chooses some of its 1-hop neighbours as re-broadcasting nodes and then forwards the broadcast packet. In reactive schemes [1, 16, 24, 27, 31, 75, 77, 82, 88, 89, 94], each node determines on its own on whether or not to forward a broadcast packet. In general, these techniques are not adaptive enough to deal with large networks and high mobility [1, 16, 24, 27]. This is due to the fact that when the network topology changes frequently, the overhead of discovering and maintaining local network topology (within 1 or 2 hops) for each node increases, and may outweigh the benefit of reduction in retransmission [1, 16, 24, 27]. Furthermore, in proactive techniques, the task of selecting a suitable set of nodes to forward the broadcasts is not trivial and requires significant computation on the mobile nodes [21, 22, 82, 90].

2.2.1.2 Clustering-Based Schemes [19]

The network is partitioned into a group of clusters forming a simple backbone infrastructure. Each cluster has one cluster head that dominates all other members in the cluster, e.g. responsible for rebroadcast and selecting rebroadcast nodes within its cluster. Although clustering can be desirable in MANETs, the overhead of cluster formation and maintenance is non-trivial in most cases [8, 13]. Therefore, the total number of transmissions (forward nodes) is generally used as the cost criterion for broadcasting. Cluster head and gateway nodes together form a connected dominating set [8, 13, 19, 30]. The problem of finding the minimum number of forward nodes is well known to be NP-complete [19, 30]. Moreover the maintenance of cluster structure, however, requires excessive communication overhead due to 'chain effect' caused by node mobility [19, 30]. Although either lowest-ID or highest node degree cluster algorithm is localized (with delayed decisions), it has no localized maintenance property. To achieve localized maintenance property, the cluster maintenance can use a different algorithm to make the update localized [8, 13, 19, 30] once the cluster is constructed, a non- cluster head will never challenge the current cluster head. If a cluster head moves into an existing cluster, one of the cluster head will give up its role as a cluster head based on some predefined priority. The localized maintenance is preserved, but at the price of increasing the number of clusters with increased node mobility [4, 6, 11, 19].

2.2.2 Distance-based Schemes [14]

Upon the reception of a previously unknown packet, a node initiates a waiting timer. Before the waiting timer expires, the node checks the location of the senders of each received packet. If any sender is closer than a threshold distance value, the node will not rebroadcast the packet. Otherwise, the node rebroadcasts it when the waiting timer expires.

Nodes using the distance-based scheme [14] compare the distance between themselves and each neighbour node that has previously rebroadcast a given packet. Upon reception of a previously unseen packet, a Random Delay (or RAD for short) is initiated and redundant packets are cached. When the RAD expires, all source node locations are examined to see if any node is closer than a threshold distance value. If true, the node does not rebroadcast. This protocol requires knowledge of neighbour locations. Signal strength could be used to gauge the distance to the source of a received packet. Alternatively, if a Global Positioning

System (GPS) is available, nodes could include their location information in each packet transmitted. The distance-based scheme succeed to reach a large part of the network but do not economise the number of broadcast packets because a node may have heard a broadcast packet for many times, but still rebroadcasts the packet as none of the transmission distances are below a given distance threshold.

2.2.3 Location-based Schemes [14]

Upon the reception of a previously unknown packet, the node initiates a waiting timer and accumulates the coverage area that has been covered by the arrived packet. When the waiting timer expires, if the accumulated coverage area is larger than a threshold value, the node will not rebroadcast the packet. Otherwise, the node will rebroadcast it.

The location-based scheme [14] uses a more precise estimation of expected additional coverage in the decision to rebroadcast. In this method, each node must have the means to determine its own location, e.g. via GPS; rebroadcast nodes add their locations to the header of the packet. When a node initially receives a packet, it notes the location of the sender and calculates the additional coverage area obtainable were it to rebroadcast. If the additional area is less than a threshold value, the node will not rebroadcast, and all future receptions of the same packet will be ignored. Otherwise, the node assigns a RAD before delivery. If the node receives a redundant packet during the RAD, it recalculates the additional coverage area and compares that value to the threshold. The area calculation and threshold comparison occur with all redundant broadcasts received.

2.2.4 Blind Flooding

Figure 2.3 outline the operation of the blind flooding algorithm [10, 14, 28, 73], where a source node broadcasts its packet to all neighbours. Each of those neighbours in turn rebroadcasts the packet the first time it receives the packet. Redundant packets are simply dropped. This behavior continues until all reachable network nodes have received. This approach offers simple implementation and reliability as its main advantage. However, blind flooding produces high overhead in the network, resulting in the broadcast storm problem [10, 18, 28].

Algorithm: Blind Flooding

Protocol receiving ()

On receiving a broadcast packet *m* at node *X* do the following:

    If packet *m* received for the first time **Then**

        broadcast (*m*)

    End if

End Algorithm.

Figure 2.3: A description of the blind flooding algorithm.

2.2.5 Counter-Based Schemes

Counter-based schemes show an inverse relationship between the numbers of times a packet is received at a node and the probability of that node being able to reach additional area on a rebroadcast. In [14], the authors have used a fixed threshold *C* (where *C* is a given number of times a given node has received a broadcast packet) to inhibit redundant rebroadcasts. If a node has already heard the same broadcast packet more than *C* times, it will not rebroadcast the packet because it is unlikely that the rebroadcast will provide new information to the node's neighbourhood. According to [14], the counter-based scheme does provide significant savings when a small threshold *C* (such as 2) is used. Unfortunately, reachability degrades sharply in a sparse network when this parameter is used, as revealed in [10, 14]. Increasing the value of *C* improves reachability, but, once again, (a metric of which is saved rebroadcasts) will suffer. To resolve the dilemma between reachability and saved rebroadcasts, in [18] the authors have proposed an adaptive counter-based scheme in which each individual node can dynamically adjust its threshold *C* based on its neighbourhood status.

2.2.6 Probabilistic Schemes

Probabilistic schemes are one of the proposed solutions to reduce redundant rebroadcasts so as to alleviate the broadcast storm problem [10, 14, 20]. Figure 2.4 outlines the operations of probabilistic flooding. In the probabilistic scheme, when receiving a broadcast packet for the first time, a node rebroadcasts the packet with a pre-determined probability *p*. The study of [14, 20] has shown that the probabilistic scheme has poor reachability. The problem comes from the uniformity of the algorithm; every node has the same probability to rebroadcast the packet, regardless of its number of neighbours. In dense networks multiple nodes share similar transmission coverage's. Thus, randomly having some nodes not rebroadcast should saves node and network resources without harming delivery effectiveness, e.g. reachability. In sparse networks, there is much less shared coverage; thus, nodes may not receive all the broadcast packets with the probabilistic scheme unless the probability parameter is high. When the probability is 100%, this scheme reduces to blind flooding.

Algorithm: Probabilistic Flooding

Protocol receiving ()
On receiving a broadcast packet *m* at node *X* do the following:

If packet *m* received for the first time **Then**

broadcast (*m*) with fixed probability *p*

End if

End Algorithm

Figure 2.4: A description of the probabilistic flooding algorithm.

Cartigny and Simplot [25] have described a probabilistic scheme where the probability *p* is computed from the local density *n* (i.e. the number of neighbours of the node considering retransmission). The authors have also introduced an efficiency parameter *k* which has a fixed value for a given network topology. However, the authors in [25] have not discussed how the parameter *k* is fixed for a particular network setup.

Zhang and Agrawal [33] have described a dynamic probabilistic scheme. They have used a combination of probabilistic and counter-based approaches. The value of a packet counter does not necessarily correspond to the exact number of neighbours from the current node, since some of its neighbours may have suppressed their rebroadcasts according to their local rebroadcast probability. In [10, 14, 18] the authors have used a fixed threshold *C* to inhibit redundant rebroadcasts. If a node has already heard the same broadcast packet more than *C* times, it will not rebroadcast the packet because it is unlikely that the rebroadcast will provide new information to the node's neighbourhood. It was shown in [10, 14, 18] that a threshold *C* of 3 of 4 can significantly reduce the redundant rebroadcast in a dense network while achieving a reachability better or comparable to that of flooding. A larger threshold C of 6 will provide less savings of redundant rebroadcast and may behave similar to flooding. Increasing the value of C improves reachability, but, once again, efficiency of the broadcast algorithm in terms of control of redundant rebroadcast will suffer. To resolve the trade-off between reachability and control of redundant rebroadcasts, there is a need for dynamic counter-based scheme in which each individual node can dynamically adjust the counter value using neighborhood information. It has been argued in [14] that the value of a packet counter does not necessarily correspond to the exact number of neighbors of the node, since some of its neighbors may have failed to rebroadcast the packet according to their local rebroadcast probability. On the other hand, the decision to rebroadcast is made after a random delay.

2.3 The Random Waypoint Model

The random waypoint mobility model [39] is one of the most popular mobility models in MANET research and in itself a focal point of much research activity [13, 38, 50, 53]. The model defines a collection of nodes which are placed randomly within a confined simulation space. Then, each node selects a destination inside the simulation area and travels towards it with some speed, meter/s. Once it has reached the destination, the node pauses for some time, pause, before it chooses another destination and repeats the process. The node speed of each node is specified according to a uniform distribution between 0 and Vmax, where Vmax is the maximum speed parameter. We have found that the general conclusions do not change much when the pause time is greater than 0 seconds. Therefore, we have opted to include only the results for 0 seconds pause time in this dissertation;

please note that the performance impact of pause times greater than 0 seconds have been analysed and the findings have been reported in [104]. It has been suggested in [43] that simulations should be left to run for some period of time before collecting data. In the initial use of the random waypoint model for evaluation [43], an increase in mobility was simulated by increasing the maximum speed parameter or decreasing the pause time.

2.4 Ad hoc On-Demand Distance Vector (AODV) routing

The AODV routing algorithm is a popular reactive routing algorithm which has been ratified by the IETF in an experimental RFC [56]. In order for the source to discover a path to a particular destination, the network is flooded with Route Request (RREQ) packets. As a RREQ packet is rebroadcasted by the intermediate nodes, the hop sequence to the destination is recorded on the RREQ packet's header. When the RREQ packet reaches the destination or a node that knows the route to the destination, a Route Reply (RREP) packet is transmitted back to the source by reversing the path of the RREQ packet, thus informing the source of the new route. The route request may take multiple paths to reach the destination, but the destination always chooses the optimum path. If one of the intermediate nodes moves then one of the moved node's neighbours realises the link failure and sends a link failure notification to its upstream neighbours and so on till it reaches the source upon which the source can reinitiate route discovery if needed.

2.5 Assumptions

In the following chapters, extensive simulation results will be presented to evaluate the performance of our suggested solutions to broadcasting in MANETs. The subsequent assumptions are used during this research and have also been extensively used in other similar existing studies, e.g. [1, 4, 10, 11, 14, 25, 27, 33, 77, 82, 88, 89, 94].

- A broadcast request can be issued by any source node which has a packet to be distributed to the whole network
- The decision to rebroadcast a packet by given node is independent of the other nodes in the network
- According to the broadcast algorithm considered in this research, a node rebroadcasts a given packet not more than one time.
- The number of nodes in a given topology remains constant throughout the simulation time. Network partitioning does not occur during simulation and so the network is connected at all times.
- Mobiles nodes have sufficient power supply to function throughout the simulation time. At no time does a mobile node run out of power or malfunction because of lack of power.
- All nodes are equipped with IEEE 802.11 transceivers.

2.6 Justification of the Method of Study

In this work extensive simulations are conducted to explore performance-related issues of probabilistic flooding in MANETs. This section briefly discusses the choice of simulation as the proper method of study for the purpose of this dissertation, justifies the adoption of ns-2 as the preferred simulator, and further provides information on the techniques used to reduce the opportunity of simulation errors.

After some consideration, simulation was chosen as the method of study in this dissertation. Particularly, when this research work was undertaken, analytical models with respect to multi-hop MANETs were considerably coarse in nature which made them unsuitable to aid the study of probabilistic flooding with a reasonable degree of accuracy; it should be noted, however, that understanding of multi-hop wireless communications has improved in recent times [103]. In addition, since the range of this study of broadcasting in MANETs involves numerous mobiles nodes, even a moderate deployment of nodes as an experimental test-bed could involve substantial and too expensive cost. As such, simulation was chosen as it provides a reasonable trade-off between the accuracy of observation involved in a test bed implementation and the insight and completeness of understanding provided by analytical modeling.

In order to conduct simulations the popular ns-2 simulator has been used extensively in this work. Ns-2 was chosen primarily because it is a proven simulation tool utilised in several previous MANET studies [14, 23, 25, 33, 43, 49, 87, 99] as well as in other network studies [37]. While developing modifications to the simulator, special care was taken in order to ensure that the algorithms implemented would function as designed and that the simulator would not exhibit unwanted side-effects; this was accomplished through meticulous use of the validation suite provided with ns-2 as well as careful piecemeal testing of implemented features. Further, real-life implementations of routing agents, such as AODV [36], were used in some of the simulations conducted in this dissertation, in order to achieve a close approximation of real system behavior.

In our simulation experiments, we could use either single broadcast node with higher rates or multiple broadcast nodes with low rates. However, we have not examined multiple broadcasts due mainly to time constraints. Having said that, these two options would be equally relevant if we were interested in evaluating the impact of the traffic load on network performance. However, since one of our aims at this stage of our research study is to analyse the behaviour of rebroadcast packets inside the network, we have decided to use a single broadcast in order to understand how packets from a given source compete with each other inside the network, and thus affect network performance in terms of reachability and saved rebroadcast.

2.7 Summary

This chapter has described the characteristics of broadcast operations in MANETs including, redundancy, collision, prevention of infinite loops, and the use of 'Hello' packet contents. The chapter has also provided a general overview of the existing broadcasting algorithms proposed in MANETs, including neighbour knowledge-based, distance-based, location-based, counter-based schemes, blind flooding, and probabilistic schemes. It then has provided a description of the random waypoint mobility model and Ad hoc On-Demand Distance Vector (AODV) routing protocol, then listed the common simulation assumptions which apply throughout this research. Finally, the chapter has provided justification on using ns-2 simulations as the method of the study in this research.

Probabilistic flooding algorithms are one of the proposed solutions to reduce redundant rebroadcasts and differentiate the timing of rebroadcasts so as to alleviate the broadcast storm problem. They are simpler and easier to implement compared to their deterministic algorithms, such as those belonging to the class of neighbour knowledge-based, distance-based, and location-based schemes. The next chapter will conduct a performance analysis of probabilistic flooding where each node re-broadcasts a packet with a fixed probability. The effects of various parameters in a MANETs are taken into consideration including node speed, pause time, density, and traffic load. The main aim of this analysis is to identify and highlight the performance limitations of this scheme in a MANET environment. The subsequent chapters will then propose new and efficient probabilistic algorithms that can overcome such limitations.

Chapter 3

Performance Analysis of Probabilistic Flooding

3.1 Introduction

A probabilistic approach to flooding has been suggested in [10, 14, 20, 40] as a means of reducing redundant rebroadcast packets and alleviating the detrimental effects of the broadcast storm problem [10, 14, 18, 40]. In the probabilistic scheme, when receiving a packet for the first time, a node rebroadcasts the packet with a pre-determined probability p; every node has the same probability to rebroadcast the packet. When $p = 1$ this scheme reduces to blind flooding.

The studies in [14, 20, 25, 40] have revealed that probabilistic broadcast incurs a lower overhead compared to blind flooding while it manages to maintain a good degree of propagation for the broadcast packets. However, when analysing the performance of probabilistic flooding these studies have not taken into consideration a number of important factors that could greatly impact the performance of a typical MANET. Such factors include node mobility, network density, and injected traffic load. There has not been so far any attempt to analyse the performance behaviour of probabilistic flooding in a MANET environment. In an effort to fill this gap, this chapter investigates the effects of mobility, injected traffic load and network density, on the effectiveness of probabilistic flooding in MANETs.

The remaining part of this chapter is organised as follows. Section 3.2 describes in detail the simulation setup. Sections 3.3 to 3.5 present performance results to show the effects of node mobility, traffic load and network density on the performance of probabilistic flooding. Finally, Section 3.6 concludes the chapter.

3.2 Simulation Setup

We have used ns-2 as the simulation platform [5]. Ns-2 is a popular discrete-event simulator which has originally been designed for wired networks and has been subsequently extended to support simulations in MANET settings. The simulation scenarios consist of 50 mobile nodes moving in a terrain of 1000X1000m. The density of the nodes is sufficient to maintain good network connectivity levels, with each node engaging in communication transmitting within 250 meter radius and having bandwidth of 2Mbps. The rebroadcasting probabilities have been varied from 0.1 to 1.0 percent with 0.1 percent increment per simulation trial and each data point for each rebroadcast probability represents an average of 30 randomly generated mobility patterns in order to achieve a 95% confidence interval in the collected statistics.

One node is selected as the data source where a CBR traffic generator has been attached to it. The random waypoint model [51] has been used to simulate 30 mobility patterns. Nodes follow a motion-pause recurring mobility state, where each node at the beginning of the simulation remains stationary for pause time seconds, then chooses a random destination and starts moving towards it with speed selected from a uniform distribution (0, max_speed]. After the node reaches that destination, it again stands still for a pause time interval (pause_time) and picks up a new destination and speed. This cycle repeats until the simulation terminates. The maximum speeds are varied from 2 to 20 m/s and pause times of 0 seconds are considered for the purpose of the present study. It is worth noting that the interface queue length has been selected because it has been used in many previous similar studies [10, 14, 18, 25, 40]. Moreover, this has been found to reduce the number of drop at the link layer protocol due to increased packet collisions. Furthomer simulation parameters used in this research study have been widely adopted in existing performance evaluation studies of MANETs [10, 14, 18, 25, 40], and are summarised below in Table 3.1.

Table 3.1: Summary of the parameters used in the simulation experiments.

Parameter	Value
Transmitter range	250 meters
Bandwidth	2 Mbps
IFQ Type Queue / DropTail/ PriQueue	50 packets
Simulation time	900 seconds
Pause time	0 seconds
packet size	512 bytes
Topology size	1000×1000 m^2
Number of node	25,50,75,100
Maximum speed	2, 4, 8 and 20 m/s

All packets with a valid source route are put in the network interface queue, which is an output queue for packets from the network protocol stack waiting to be transmitted by the network interface. This queue is used to hold packets while the network interface is in the process of transmitting another packet. Broadcast protocols maintain a send buffer of 50 packets, which holds all data packets without a source route. The packets waiting in the send buffer for more than 30 seconds are dropped. All packets from the routing layer are queued at the interface queue waiting for MAC layer to transfer. The interface queue is FIFO scheduling policy. The size of the queue is 50 packets as defined in a mobile node configuration; it is worth noting that we have selected such a queue size because it has been used in many previous similar studies that have used in the previous research [10, 14, 25]. Moreover, this length has been found to reduce the number of drops at the link layer protocol due to increased packet collisions.

The performance of a broadcast protocol can be measured by a variety of metrics [10, 14, 18, 25, 33, 40]. A commonly used metric is the number of packet re-transmissions with respect to the number of nodes in the network [10, 14, 17, 18, 25, 31, 40]. In this research work, we use saved rebroadcasts and reachability. Saved rebroadcast and reachability are often computed as follows [10, 14, 18, 25, 33, 40]

Saved ReBroadcast (SRB): is computed as $(r-t)/r$ where r is the number of nodes receiving the broadcast packet, and t the number of nodes that really transmitted the packet [10, 14, 18, 25, 33, 40].

Reachability (RE): is the percentage of number of mobile nodes receiving the broadcast packet over the total number of mobile nodes that are reachable, directly or indirectly [10, 14, 18, 25, 33, 40].

It is worth mentioning that all the statistics reported in this research have been gathered using 95% confidence intervals. For instance, the reachability results along with the associated 95% confidence intervals and relative error bars depicted in Table 3.2 have been produced for a network size of 50 nodes averaged over 30 different topologies. The relative error is the margin of error of the confidence interval that is defined to be the value added or subtracted from the sample mean which determines the length of the interval divided by the average reachability given in Table 3.2 also the relative errors bars have also been included in Figure 3.3 shown below. Nonetheless, we have to state that we have opted not to include the information on the confidence intervals and error bars in most of the performance results reported in the thesis for the sake of clarity and neatness of the figures.

Table 3.2: The mean and confidence interval for reachability (RE) for various rebroadcast probability.

Probability	Average RE	95% Confidence interval	Relative error
1	97.1	[96.70-97.49]	0.004
0.9	96.02	[95.65-96.38]	0.004
0.8	95.01	[94.55-95.46]	0.005
0.7	92.1	[91.43-92.76]	0.007
0.6	90.12	[89.33-90.90]	0.009
0.5	78.5	[77.74-79.25]	0.010
0.4	70.23	[69.19-71.26]	0.015
0.3	65	[63.90-66.09]	0.017
0.2	55.01	[53.82-56.19]	0.022
0.1	45.45	[44.30-46.59]	0.025

It is well known that blind flooding has the worst SRB nearly 0 and the best level of reachability is close to 100%. However, this is achieved at the expenses of excessive redundant re-broadcasting packets. So our objective in this research is to improve SRB while keep the same level of reachability. Figure 3.1 explores SRB at low mobility conditions of maximum speeds of 2 m/s and 0 pause time. The rebroadcast probabilities have been varied from 0.1 to 1.0 percent with 0.1 percent increment when 5 broadcast packets/s are injected into the network. Examining the results reveals that SRB decreases as the rebroadcast probability increases. For instance, when p=0.1 SRB is around 90% and when p is increased to 0.7 SRB decreases to 30%. When p=1 (blind flooding) SRB is 0%. This is because as the probability of the transmission increases for every node, this implies that there are more candidates for broadcast re-transmissions in a given area, and as a result the number of nodes that transmit the packet increases which increases the number of redundant rebroadcast packets and that leads to a higher chance of collision and contention due to the increases in redundant rebroadcast packets.

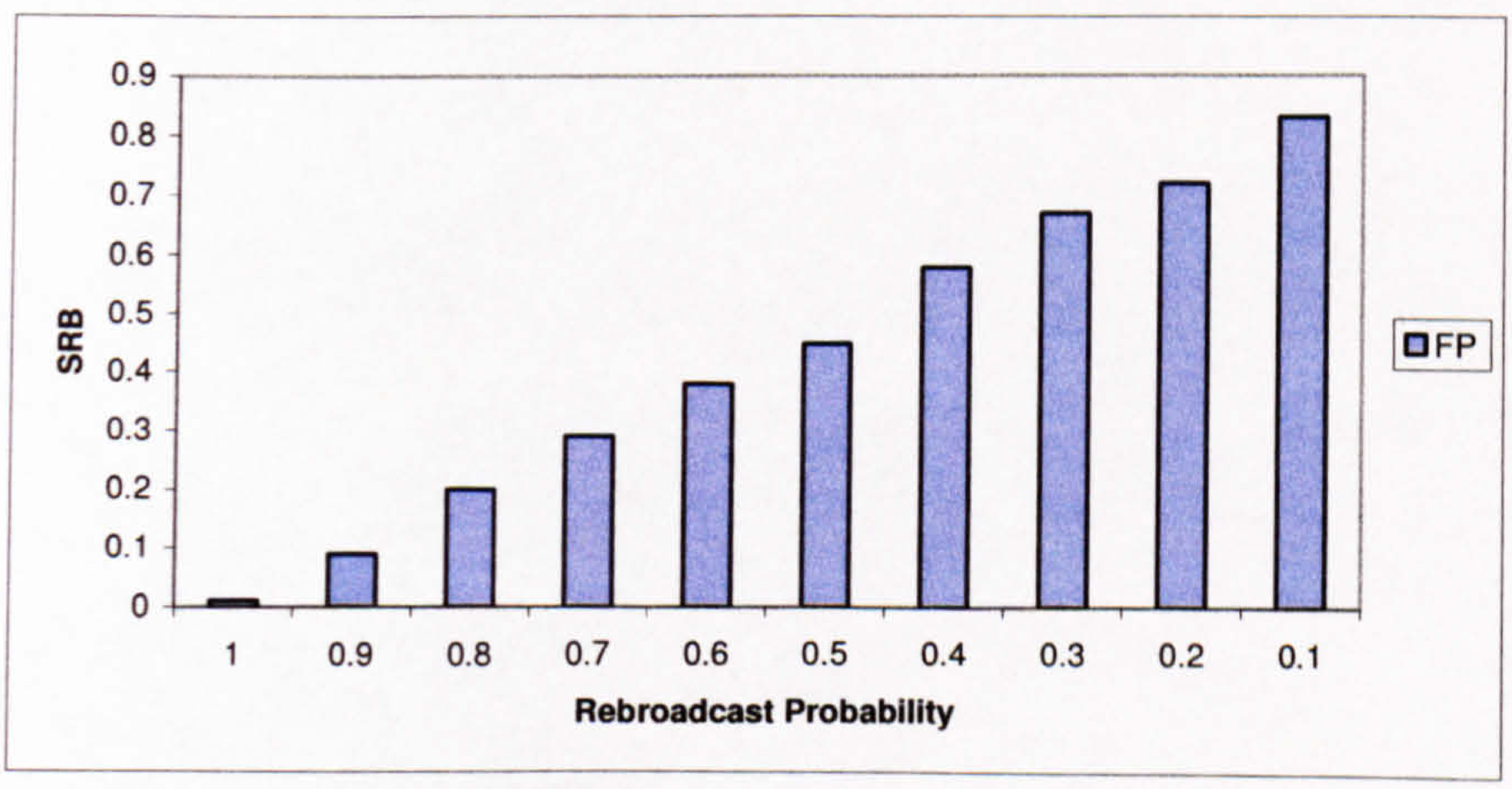

Figure 3.1: SRB vs. rebroadcast probability for a network size of 50 nodes and a node speed 2 m/s.

Figure 3.2 explores reachability (RE) of fixed probabilistic flooding for low mobility conditions of maximum speeds of 2 m/s and 0 pause time. The rebroadcast probabilities have been varied from 0.1 to 1.0 percent with 0.1 percent increment. The figure shows that RE increases as the rebroadcast probability increases. For instance when p=0.1 RE is close to 45% and when p is increased to 1.0 RE is close to 100%. This is because as the probability of the transmission increases for every node, this implies that there are more candidates for broadcast re-transmissions in a given area, and as a result the number of nodes which really transmit the packet increases which increases the number of nodes receiving the broadcast packet over the total number of mobile nodes that are reachable.

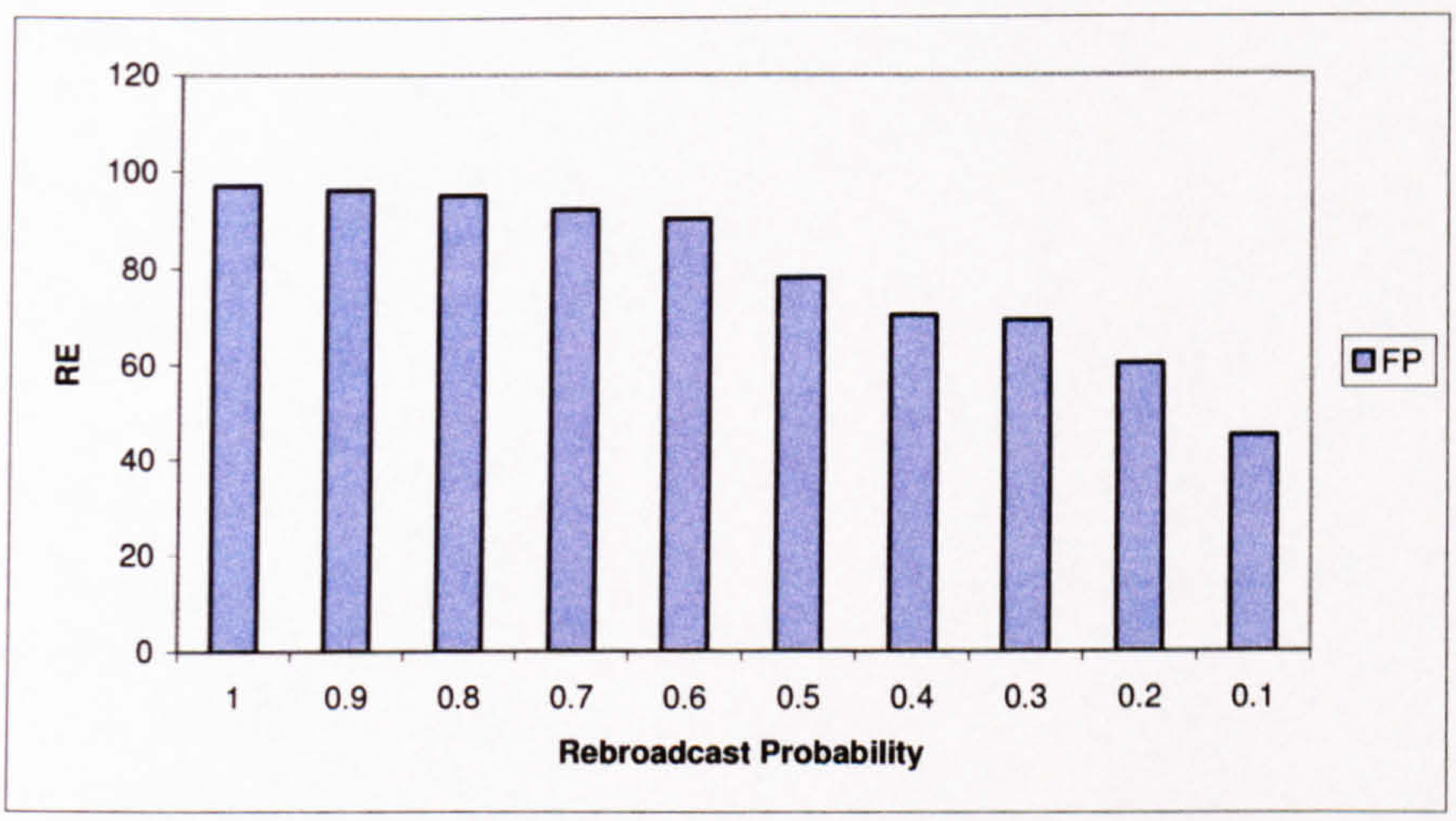

Figure 3.2: RE vs. rebroadcast probability for a network size of 50 nodes and node speed 2 m/s.

3.3 Effects of Mobility

The results for SRB achieved by probabilistic flooding for different rebroadcast probabilities are depicted in Figure 3.3. The nodes move continuously (i.e., 0 sec pause time) where the maximum speed are varied from 2 to 20 m/s. As the results show, the node speed has an impact on the observed saved rebroadcast value since for a given rebroadcast probability as the node speed increases SRB decreases. For example, SRB decreases by 9% when node speed increases from 2 to 20 m/s at the rebroadcast probabilities p=0.6 and to 0% when p=1. The drop of SRB is caused by the fact that the movement of nodes may incur an increase in the retransmission rebroadcast packets. This in turn makes the number of nodes that really transmit the rebroadcast packet increases resulting in a lower SRB.

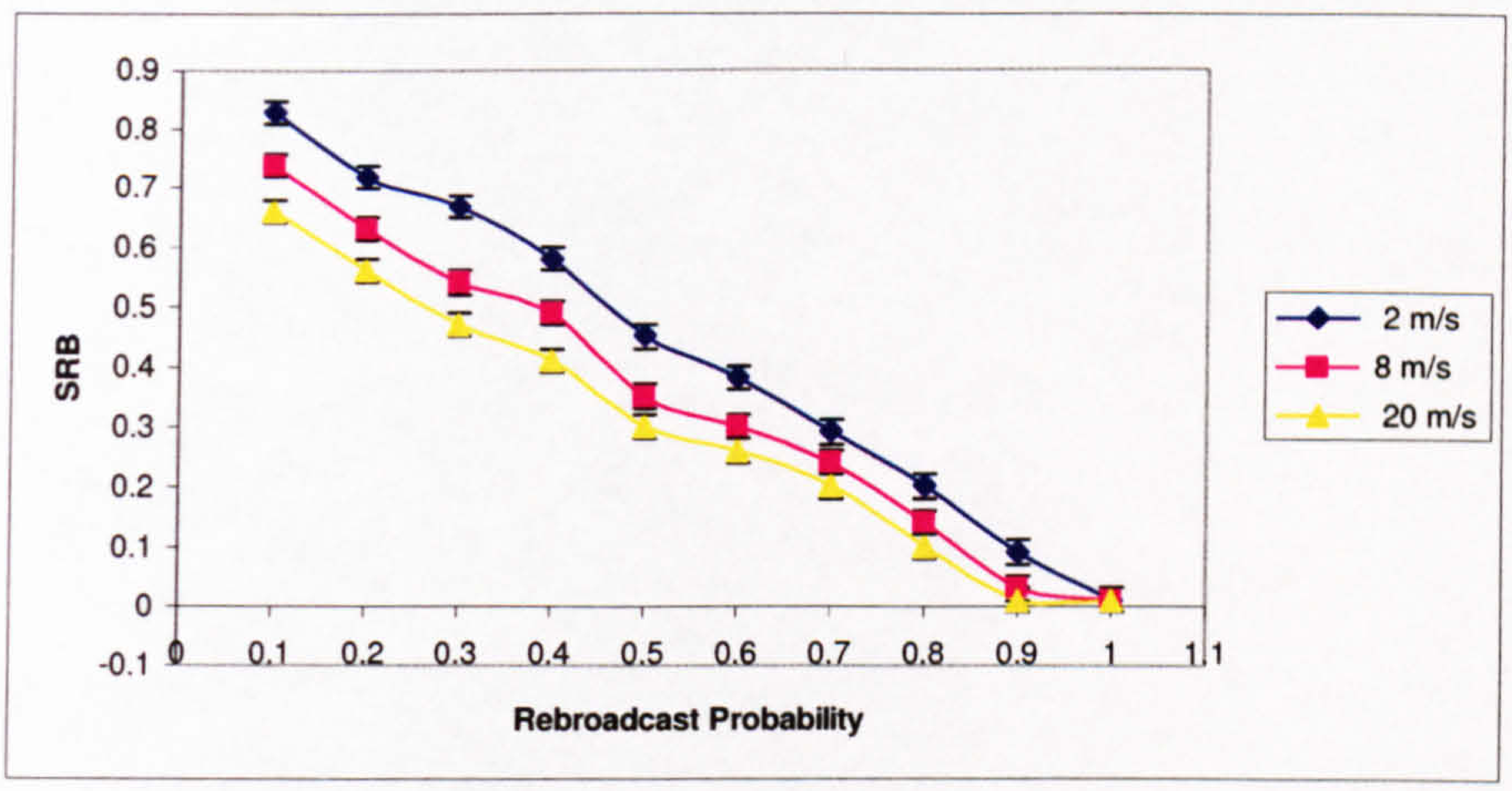

Figure 3.3: SRB vs. rebroadcast probability for different node speeds 2, 8, and 20 m/s.

Figure 3.4 shows RE against the rebroadcast probability for three different node speeds and continuous mobility. Overall, across the different rebroadcast probabilities, RE increases as the node speed increases. For example RE is 100% when the rebroadcast probability p=0.6 and when the nodes move with a high speed of 20 m/s. However, to achieve the same level of RE when nodes move at a lower speed 2 m/s, the rebroadcast probability has to be over 0.9. This is due to the fact that as the node speed increases network connectivity increases resulting in a larger number of nodes receiving the broadcast packet which causes RE to increase. However at a low speed and a rebroadcast probability p=0.6, the number of nodes receiving the broadcast packet decreases, and thus so does RE. When the node speed is low, the rebroadcast probability has to be set higher (e.g. p=0.9) in order to maintain a good reachability level.

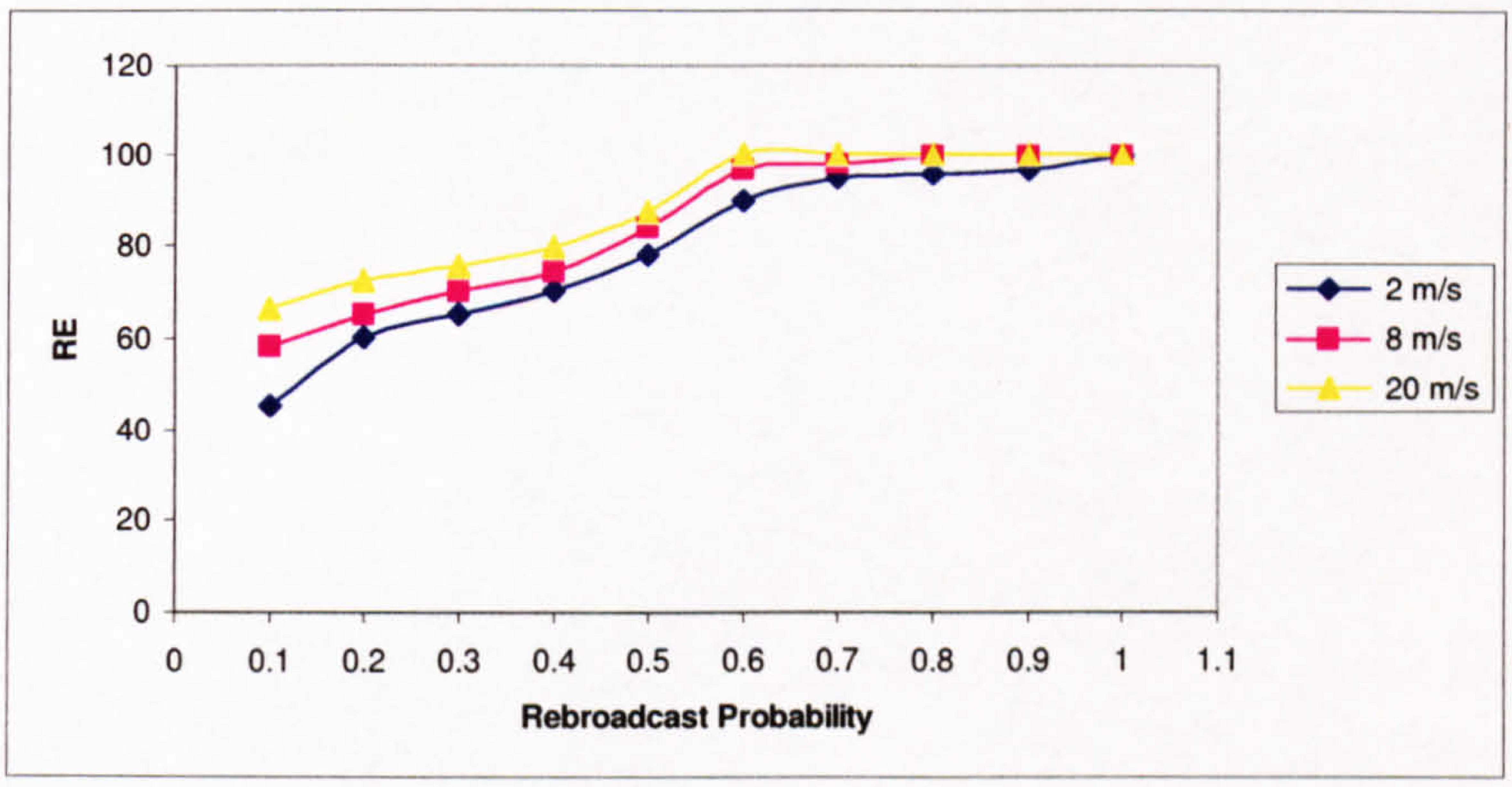

Figure 3.4: RE vs. rebroadcast probability for different node speeds 2, 8, and 20 m/s.

3.4 Effects of Traffic Load

We have varied the traffic load in the network from light traffic through moderate to heavy traffic. To do so, the following rates of broadcast packets generated at the source node are considered:

-Light traffic load: 1 packet/s;

- Medium traffic load: 5 packets/s;

- Heavy traffic load: 10 packets/s.

Figure 3.5 shows SRB as a function of the rebroadcast probability when the traffic load is varied by increasing the rate of broadcast packets from 1, 5, and 10 packets/s while the system size is kept at 50 nodes under continuous mobility conditions (0 second pause time) with the node speed of 2 m/s. The figure suggests that for continuous mobility and a speed of 2 m/s as the rebroadcast probability increases and the traffic load increases SRB increases. However SRB starts to decreases when the network is subjected to heavy traffic loads and high rebroadcast probability. For instance when p=0.8 SRB is the same for three traffic loads that because under higher traffic loads, it is more difficult to maintain a high SRB level when the rebroadcast probability is high. This is because as the load of the nodes increases, thus the number of packets present inside the network increases, and as a consequence there is a high chance for increased number of collisions as well as reduced access the shared wireless medium. This reduces the number of nodes receiving the broadcast packet, and therefore reduces SRB.

SRB has also been examined for a high node speed of 20 m/s and different traffic loads. Figure 3.6 reveals that for a given rebroadcast probability SRB is slightly affected as the node speed increases. This is due to the increased number of collisions as well as the reduced channel access when the network is subjected to increased traffic loads.

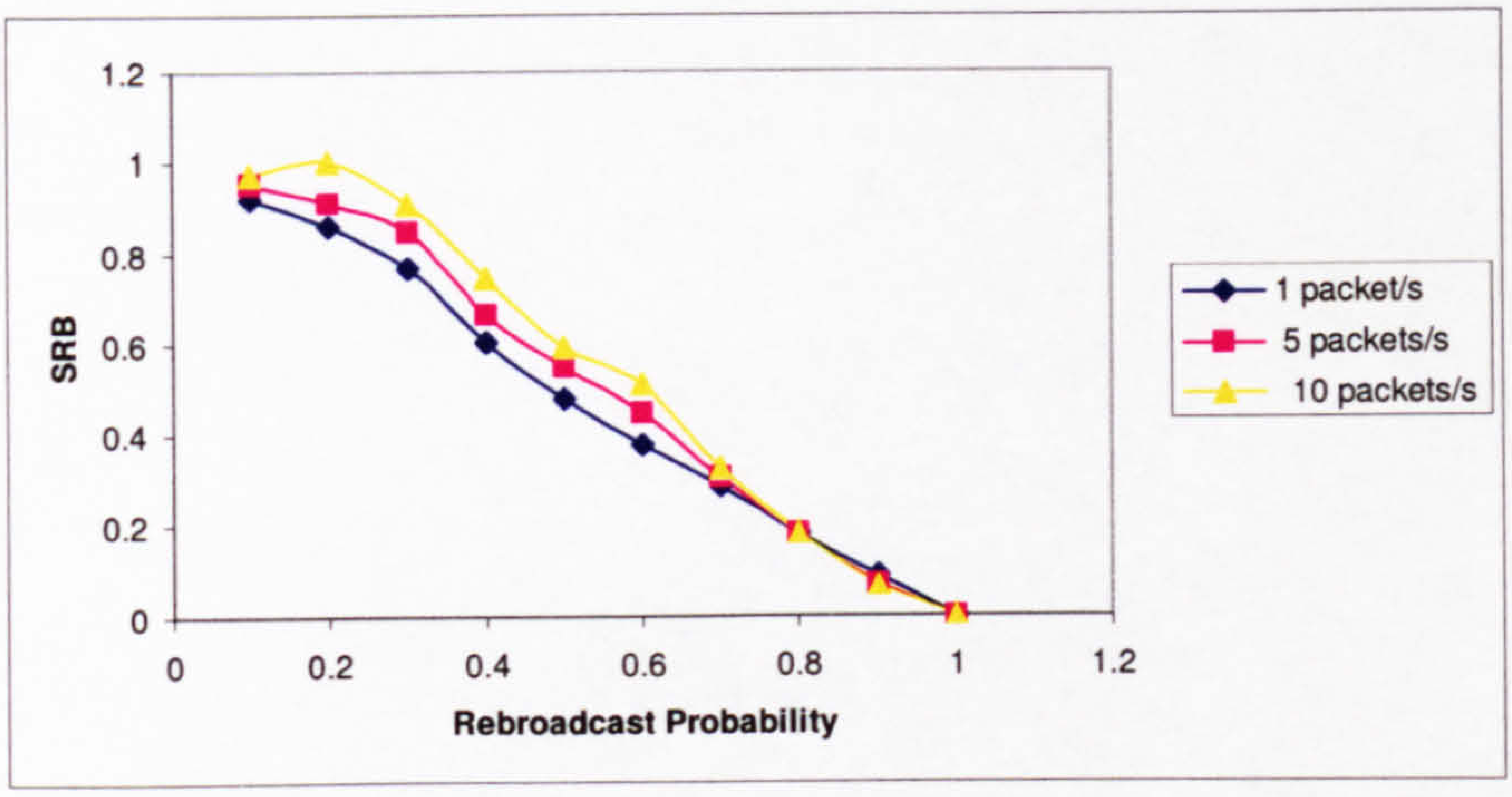

Figure 3.5: SRB vs. rebroadcast probability for different traffic loads 1, 5 and 10 packets/s and node speed of 2 m/s.

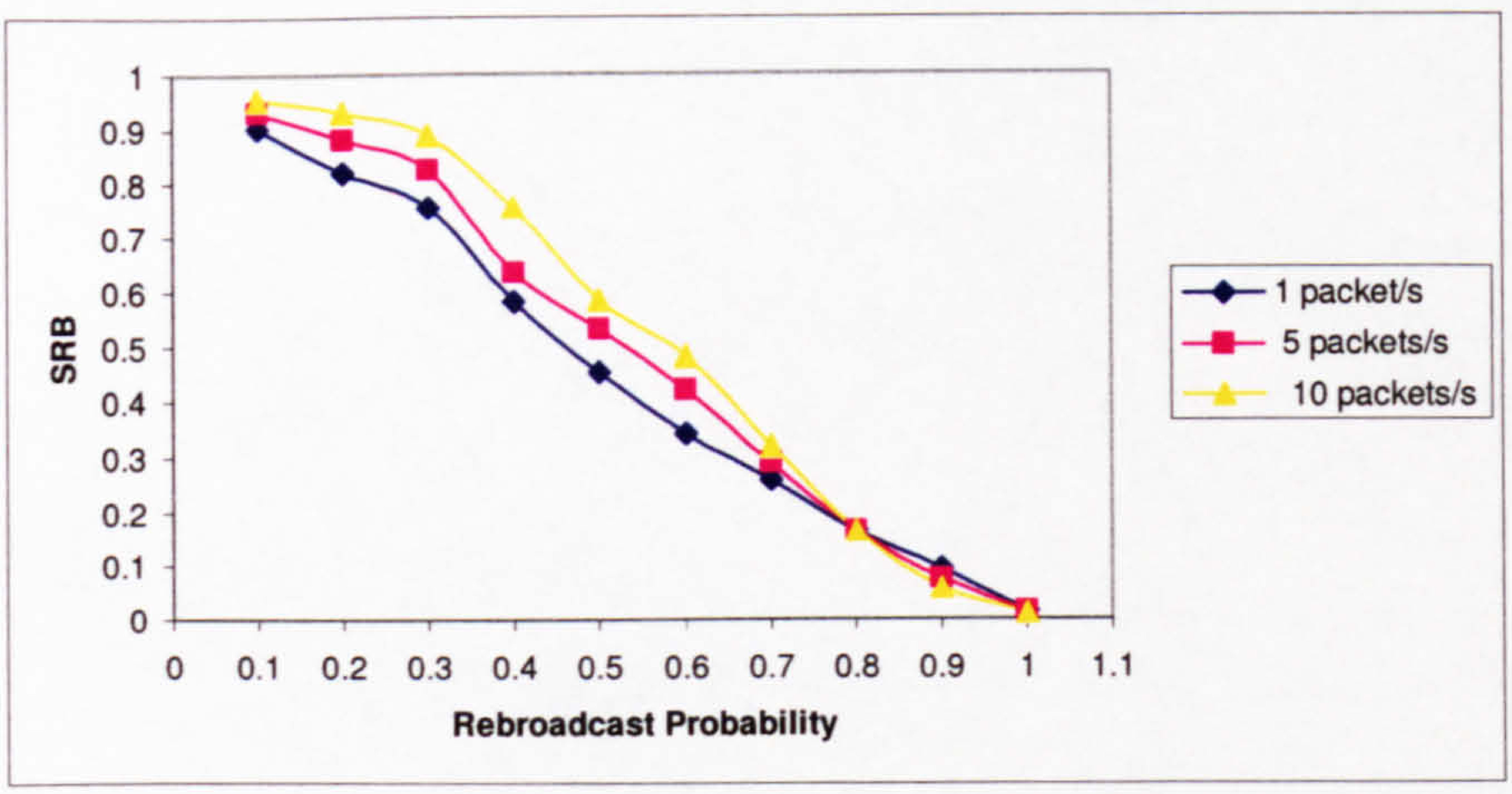

Figure 3.6: SRB vs. rebroadcast probability for different traffic loads 1, 5 and 10 packets/s and node speed of 20 m/s.

Figure 3.7 shows RE results for a varying rebroadcast probability when the traffic is varied under continuous node mobility and a speed of 2 m/s. Figure 3.7 reveals that the achieved RE increases as rebroadcast probability increases when the traffic load is light. Moreover when the rebroadcast probability is over 0.7, RE is over 95%. However, as the traffic load increases the rate of increase in RE slows down. This occurs due to the increase in the total number packets transmitted on the wireless channel which increases the number of collisions as well as reduced channel access. RE has also been examined at a high node speed. Figure 3.8 shows that in general RE is not affected that much when the node speed increases, especially as the traffic load becomes heavy. This is due to the same reason given above; i.e. due to the increased number of collisions as well as reduced channel access.

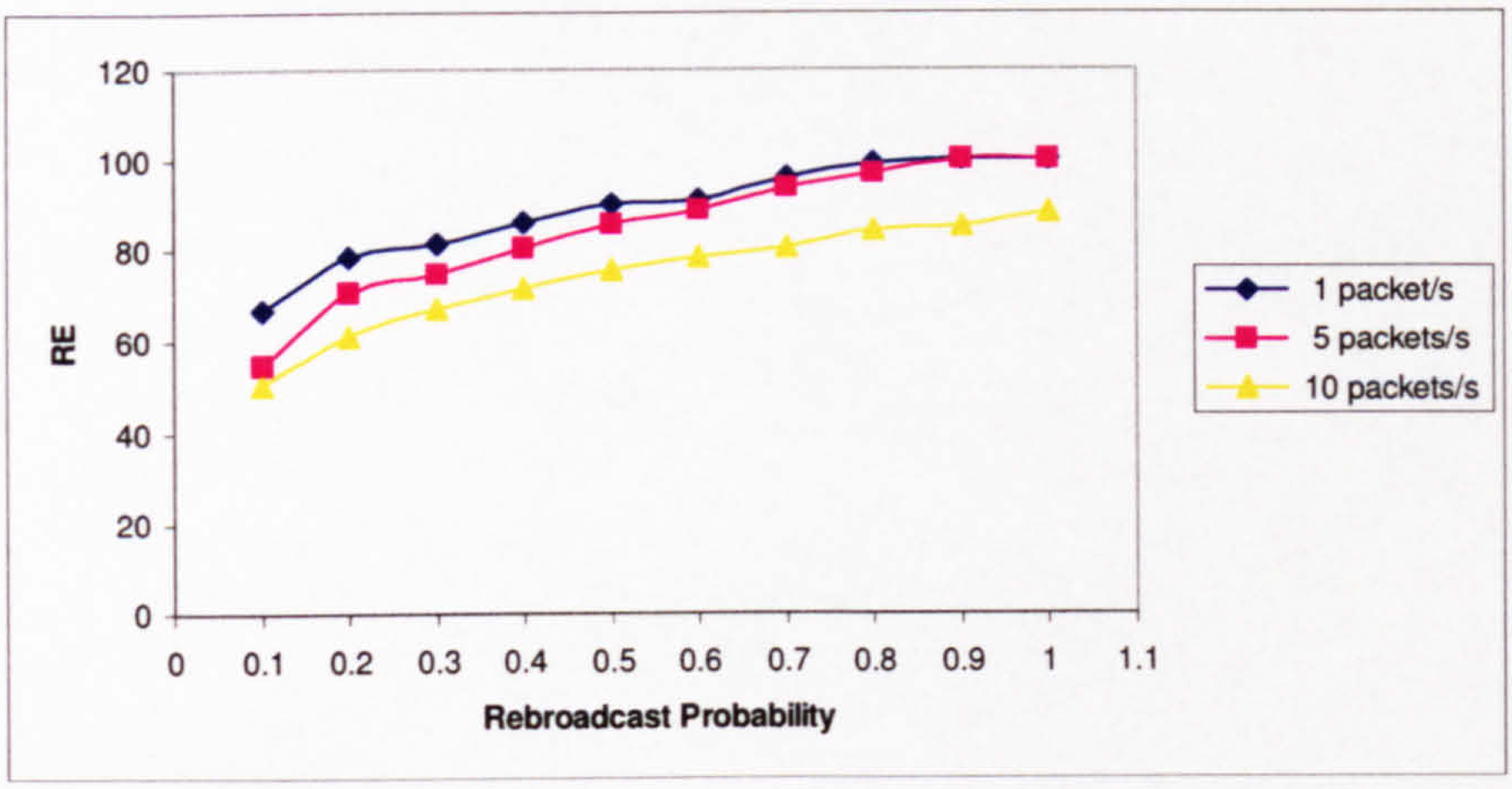

Figure 3.7: RE vs. rebroadcast probability for different traffic loads 1, 5 and 10 packets/s with a node speed of 2 m/s.

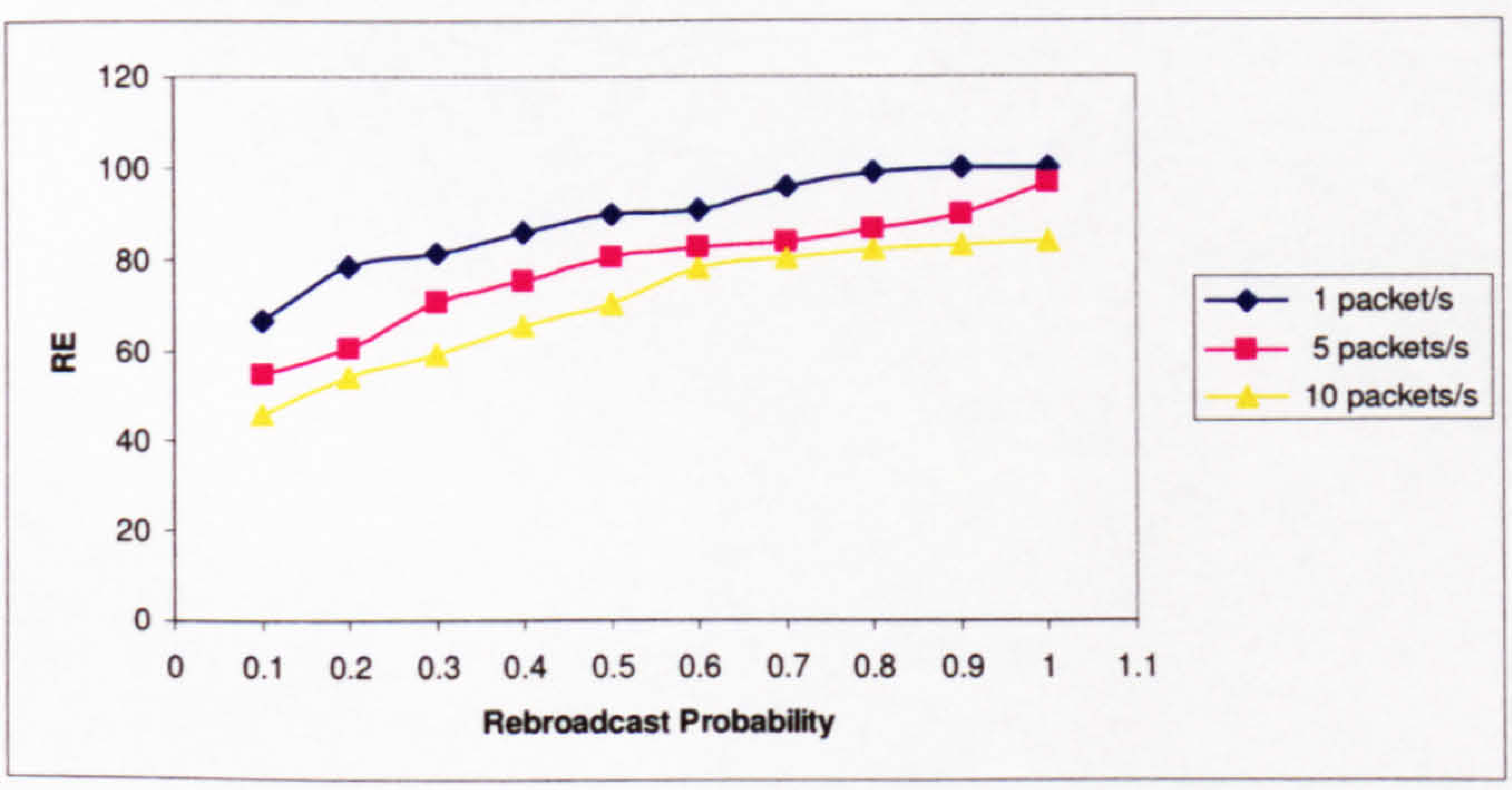

Figure 3.8: RE vs. rebroadcast probability for different traffic loads 1, 5 and 10 packets/s with a node speed of 20 m/s.

3.5 Effects of Network Density

To study the performance effects of varying network density, i.e. the number of network nodes per unit area for a given transmission range, the following three relative levels of network density are examined:

- Low density: 25 nodes;
- Medium density: 50 nodes;
- High density: 100 nodes.

Figures 3.9 and 3.10 demonstrate the effects of speed and density on SRB using 6 combinations of node densities and speeds. As can be seen in the figures, SRB increases with a higher network density. As the probability of the transmission is fixed for every node, this implies that there are more candidates for broadcast re-transmissions in a given area, and as a result there is a higher chance that a re-transmission occurs, increasing the number of SRB for a given rebroadcast probability. However, as the node speed increases, SRB decreases. Examining the figures reveals that SRB decreases as the rebroadcast probability increases. This is due to the fact that increasing the rebroadcast probability increases the number of redundant rebroadcast packets; this occurs when a node rebroadcasts a packets which its neighbour nodes have already received a copy. Furthermore, increasing the rebroadcast probability increases the chance for simultaneous transmissions leading to possible collisions.

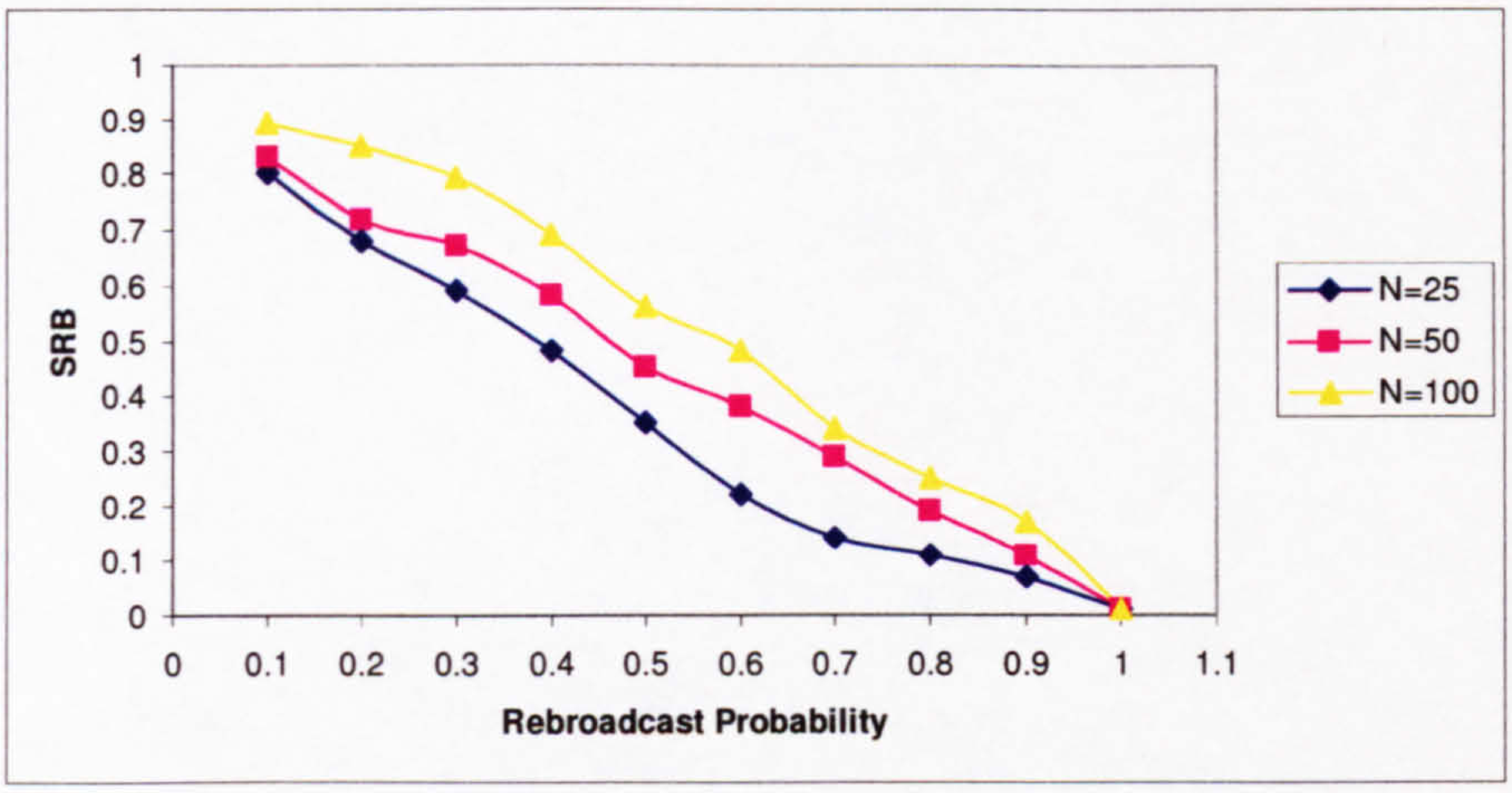

Figure 3.9: SRB vs. rebroadcast probability for different network densities 25, 50, 100 nodes and node speed 2 m/s.

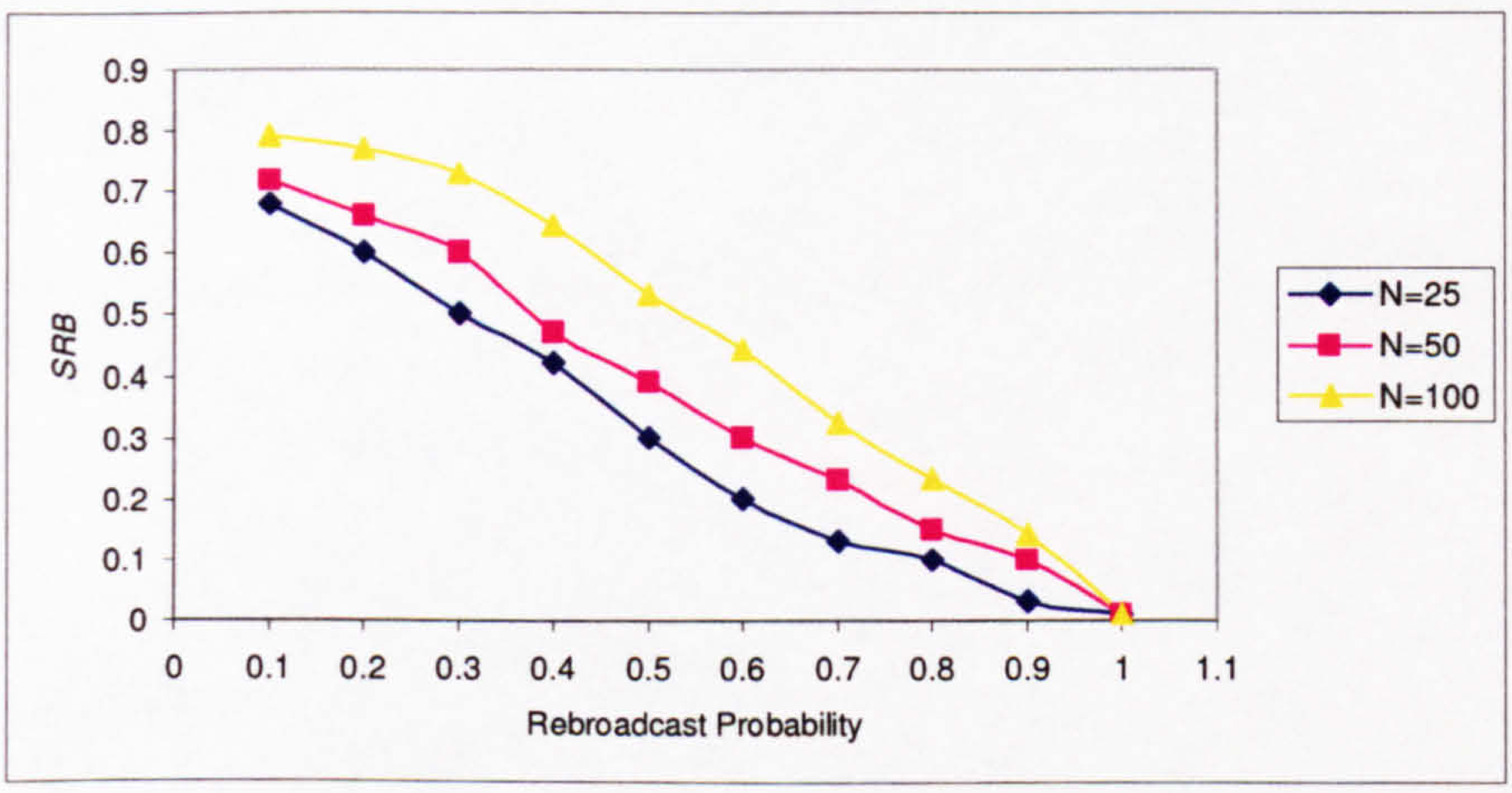

Figure 3.10: SRB vs. rebroadcast probability for different network densities 25, 50, 100 nodes and node speed 20 m/s.

Figures 3.11 and 3.12 depict the results for RE considering the three different network densities and two different node speeds. The figures suggest that RE increases with a higher network density. The trend in the figures also suggests that the reachability increases as the node speed increases. RE improves with higher density and faster moving nodes for the following reasons. As the density of the nodes increases, the number of nodes covering a particular area also increases. As the probability of re-broadcast is fixed for every node, this implies that there are more candidates for transmission in each "coverage "area. Hence, there is a greater chance that a broadcast re-transmission occurs, resulting in increased RE.

For a given transmission range, as the network density increases network connectivity increases. As a result, a small re-broadcasting probability, *p*, is sufficient to achieve a high RE. For example, *N*=100 and the probability *p*=0.6 are sufficient to achieve RE of 100%. However, a larger *p* is required if the node distribution is sparse. RE increases proportionally to *p*, as *p* increases. For example, when *N*=25 the probability *p*=1.0 is required to achieve RE of 85%. Further, as the node speed increases connectivity increases then the probability of partitioning decreases, leading to a higher RE.

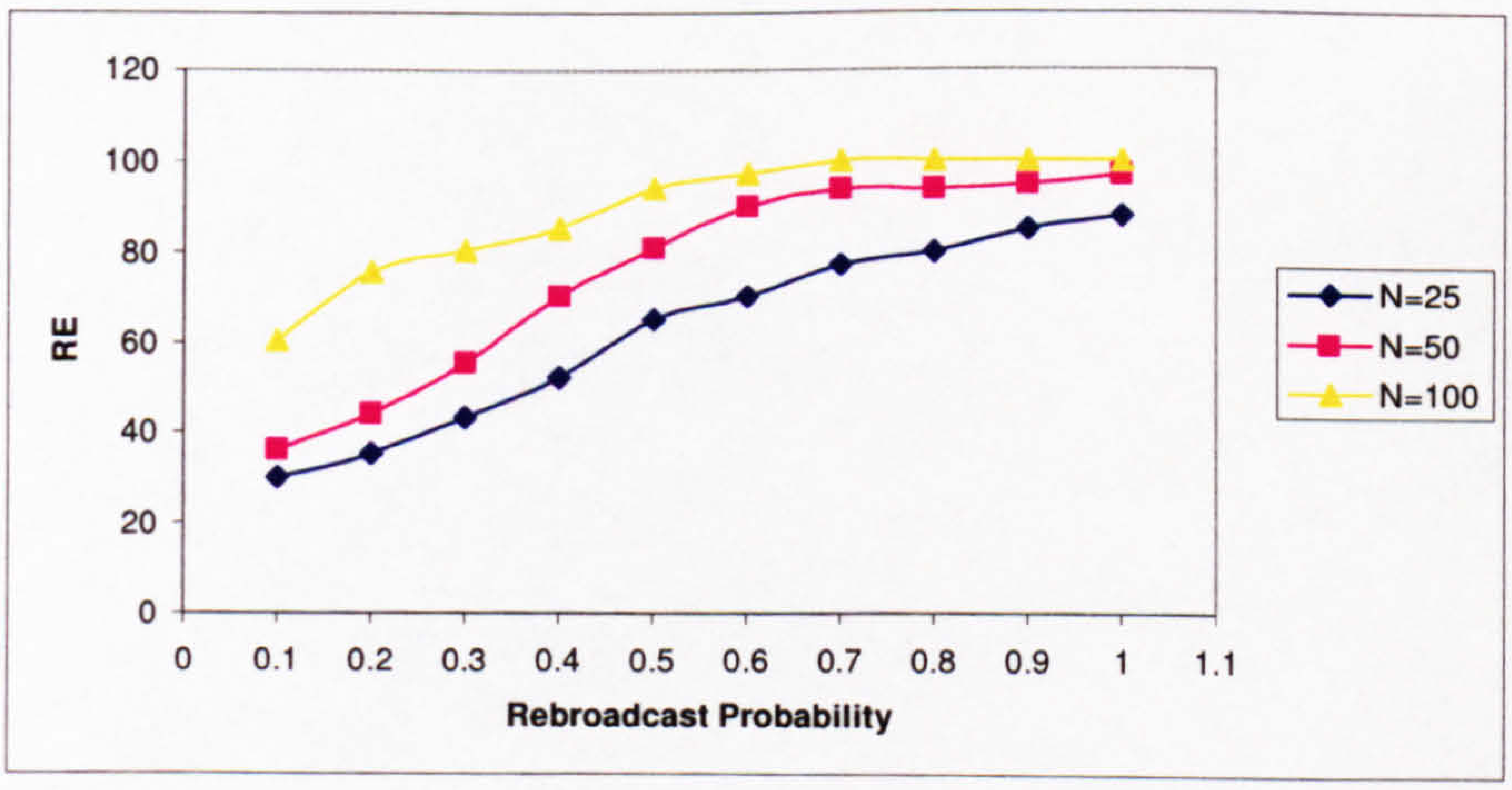

Figure 3.11: RE vs. rebroadcast probability for different network densities 25, 50, and 100 nodes and a node speed 2 m/s.

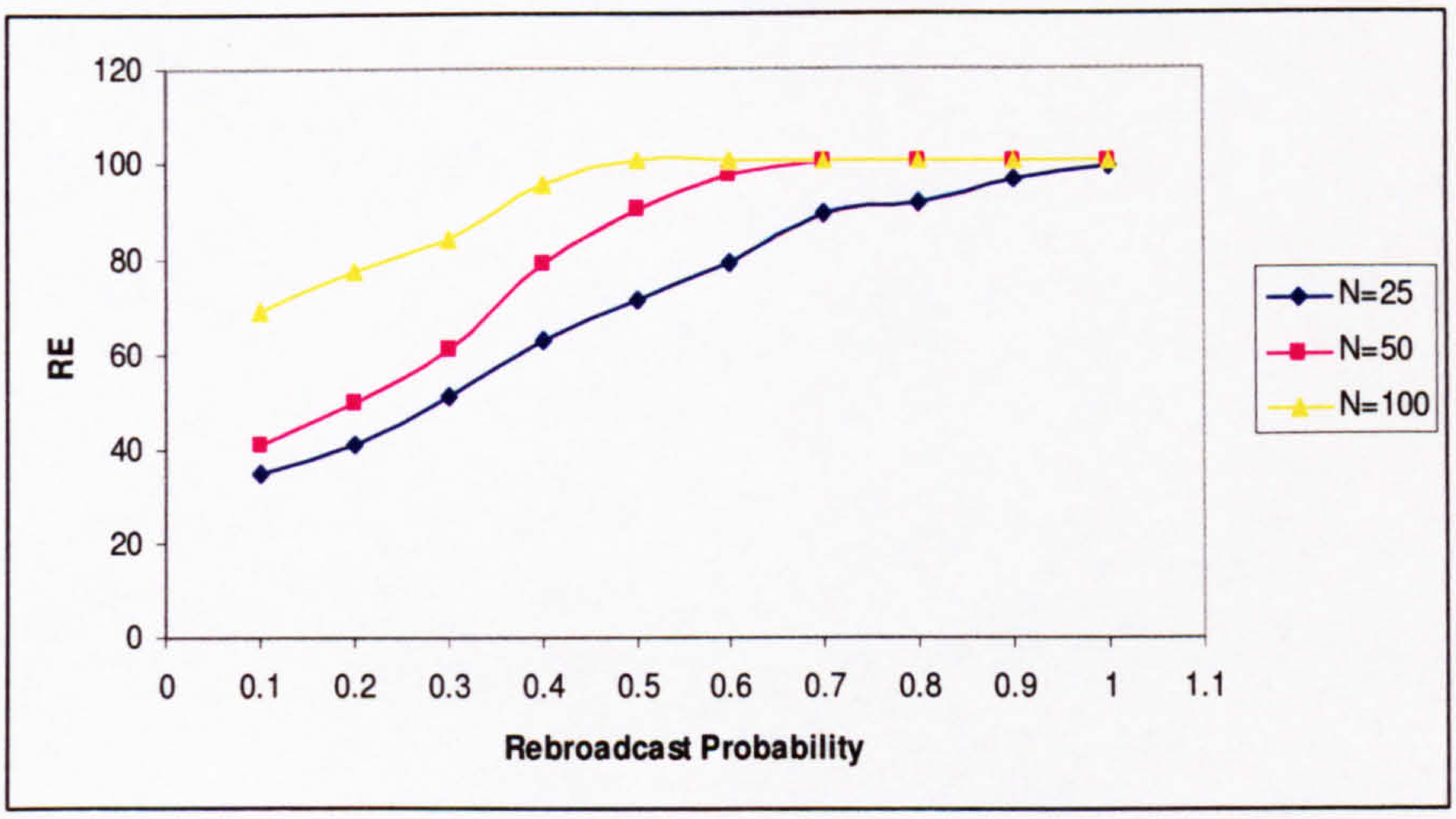

Figure 3.12: RE vs. rebroadcast probability for different network densities 25, 50, and 100 nodes and a node speed 20 m/s.

3.6 Conclusions

This chapter has analysed the effects of some of the most important system parameters in MANETs, including node mobility, traffic load, and density on the performance of the probabilistic flooding (or broadcasting). Results from ns-2 simulations have revealed that mobility have a substantial effect on the reachability and saved rebroadcast metrics. The results have shown that for different rebroadcast probabilities, as the node speed increases, saved rebroadcast decreases. For example the saved rebroadcast decreased by 10% when the node speed increases from 2 to 20 m/s. Similar performance trends have been observed when the other important system parameters, notably network density have been examined in that they have been found to have a great impact on the degree of reachability and the number of saved rebroadcasts achieved by the probabilistic broadcasting scheme. For example, reachability improves by 15% as the node density increases from 25 to 100 nodes. Moreover, reachability increases by 10% when the node speed increases from 2m/s to 20m/s.

The subsequent chapter will describe a new broadcasting algorithm that can dynamically adjust the re-broadcast probability to take into account the current state of the nodes (e.g. the current number of neighbours) in order to ensure a certain level of control over re-broadcasting, and thus helps to improve saved rebroadcasts and maintain high reachability levels.

Chapter 4

Neighbourhood Characteristics in MANETs

4.1 Introduction

The results presented in Chapter 3 have revealed that most of the important system parameters considered in the analysis, e.g. node mobility, density, and traffic load, have an impact on network performance. In MANETs, where the topology can change frequently, the rebroadcast probability at each node should be dynamically adjusted to account for a given node's surrounding in order to ensure a high performance. As a rule of thumb, the rebroadcast probability should be set high at the nodes located in sparse areas and low for nodes located in dense areas.

A straightforward method for gathering neighbourhood information at a given node involves the periodic exchange of 'Hello' packets between neighbours to construct a 1-hop neighbour list at the nodes. A high (low) a number of neighbours implies that the node in a dense (sparse) area. The higher is the number of neighbours, the denser the network area is. The lower the number of neighbours is sparser the network area is. We will show in the subsequent chapter that neighbourhood information such as the minimum, average, maximum number of neighbours of the node can be used to efficiently estimate the rebroadcast probability at the network nodes.

In this chapter, we report results from ns-2 simulations in order to characterise neighbourhood information, such as the minimum, average and maximum number of neighbours of a given node by means of 'Hello' packet exchanges. We also investigate the effects of node mobility and network density on such gathered information. Our study is motivated by the fact the periodic 'Hello' packet for ad-hoc networks stems from the hello protocol of AODV [36]. Such a protocol and its utility have been explicitly studied by Chakeres *et al.* [74]. The authors have studied the hello protocol in 802.11 ad-hoc networks but have focused on a limited type of information (i.e., connectivity or forward a packet). We will show in the subsequent chapter how we use the findings of this chapter to introduce new and efficient class of probabilistic flooding algorithm for MANETs.

The remainder of this chapter is organised as follows. Section 4.2 introduces 'Hello' packets. Section 4.3 uses ns-2 simulations to investigate the topological characteristics of MANETs. Finally, Section 4.4 provides a summary of this chapter.

4.2 'Hello' Packets

'Hello' packets are a special control packet that is sent out periodically from a node to establish and confirm network adjacency relationships and responsible for establishing and maintaining neighbor relationships. When a node receives a 'Hello' packet from its neighbour, it creates or refreshes the routing table entry to the neighbour. To maintain connectivity, if a node has not sent any broadcast control packet within a specified interval, a 'Hello' packet is locally broadcast (over one hop radius). This results in at least one 'Hello' packet transmission during every time period. Failure to receive any 'Hello' packet from a given neighbour for several time intervals indicate that neighbour is no longer within transmission range, and connectivity is assumed to have been lost.

The information contained in the 'Hello' packet varies depending on its intended usage. Thus it is necessary to quantitatively compare the size of the 'Hello' packets when analysing overhead and performance tradeoffs. A common element of the 'Hello' packet is the *ID* (four bytes) of the node that is broadcasting the packet. The node *ID* is sufficient for neighbour discovery and link detection. However, if nodes use their neighbour table for forwarding packets, then the position of the node (typically two integers) might be necessary.

In order to construct a local view of a given node's vicinity, 1-hop information based on, for instance, the minimum, average, maximum number of neighbours can be used. The selection of the time interval for the exchange of 'Hello' packets is usually set at 1 second as recommended in the AODV protocol [36, 56], OLSR [41] and TORA [35]. A node assumes that a particular neighbour has moved away and is currently outside transmission range if 'Hello' packet has not been received from that neighbour for the last two seconds, as is suggested in the AODV, OLSR and TORA protocols [35, 36, 41, 56]. In order to study the effect of mobility and network density on the collected statistics, we have considered different maximum node speeds from 2 to 20 m/s and varied the network size from 25 to 125 nodes.

4.3 Performance Evaluation

The parameters used in the following simulation experiments are listed in Table 4.1. Each node in the network has a constant transmission range of 250 meter. The MAC layer scheme follows the IEEE 802.11 MAC specification. We have used the broadcast mode with no RTS/CTS/ACK mechanisms for all packet transmissions, including Hello, DATA and ACK packets. The interface queue length has been selected because it has been used in many previous similar studies [10, 14, 18, 25]. Moreover, this has been found to reduce the number of drop at the link layer protocol due to increased packet collisions. The movement pattern of each node follows the random way-point model. Each node moves to a randomly selected destination with a constant speed between 0 and the maximum speed. When it reaches the destination, it stays there for a random period and starts moving to a new destination.

We have varied the network density (i.e., the number of nodes on a given terrain size) and have measured the minimum, average and maximum number of neighbours over the whole nodes in the network. For each configuration, we have gathered statistics for 30 arbitrary topologies where nodes are initially placed randomly over the terrain. The results represent the average over the 30 different topologies in order to achieve a 95%

confidence interval in the collected statistics. For a given number of nodes, three terrain sizes have been considered: 600m × 600m, 800m × 800m and 1000m ×1000m.

Table 4.1: Summary of the parameters used in the simulation experiments.

Parameter	Value
Transmitter range	250 meters
Bandwidth	2Mbps
IFQ Type Queue /DropTail /PriQueue	50 packets
Simulation time	900 seconds
Pause time	0 seconds (continuous mobility)
'Hello' packet size	12 bytes
Topology size	600m × 600m, 800m × 800m and 1000m ×1000m
Number of node	25, 50, 75, 100, 125
Maximum speed	2 and 20 m/s

Figures 4.1, 4.2 and 4.3 depict the minimum, average, and maximum number of neighbours after averaging over the whole network nodes when the nodes move at the max. speed of 2m/s. Various network densities resulting from a combination of different network sizes (from 25 to 125 nodes) and terrain sizes (600m×600m, 800m×800m, and 1000m×1000m) have been examined. A summary of the minimum, average and maximum number of neighbours is listed in Table 4.2. Also a summary of confidence intervals, margin errors for the minimum, average and maximum number of neighbours of a given node (averaged over the whole network) is shown in Table 4.3. The results show that as expected the denser the network is, the higher the maximum number of neighbours is at a given node. On the other hand, the sparser the network is, the lower is the minimum

number of neighbours at a given node. As the network size increases so does the minimum, average, and maximum number of neighbours. For example, in a terrain size of 1000m × 1000m when the network size is 50 nodes, a typical node has the minimum number of neighbours equals to 4, the average number of neighbour to 11, the maximum number of neighbour to 17. When the network size is doubled to 100 nodes, a typical node has the minimum number of neighbours equals to 7, the average number of neighbour to 22, the maximum number of neighbour to 34.

Figures 4.4 to 4.6 provides further results on the minimum, average and maximum number of neighbours (averaged over the whole network) after repeating the above simulation experiments where the node speed is set at 2 m/s.

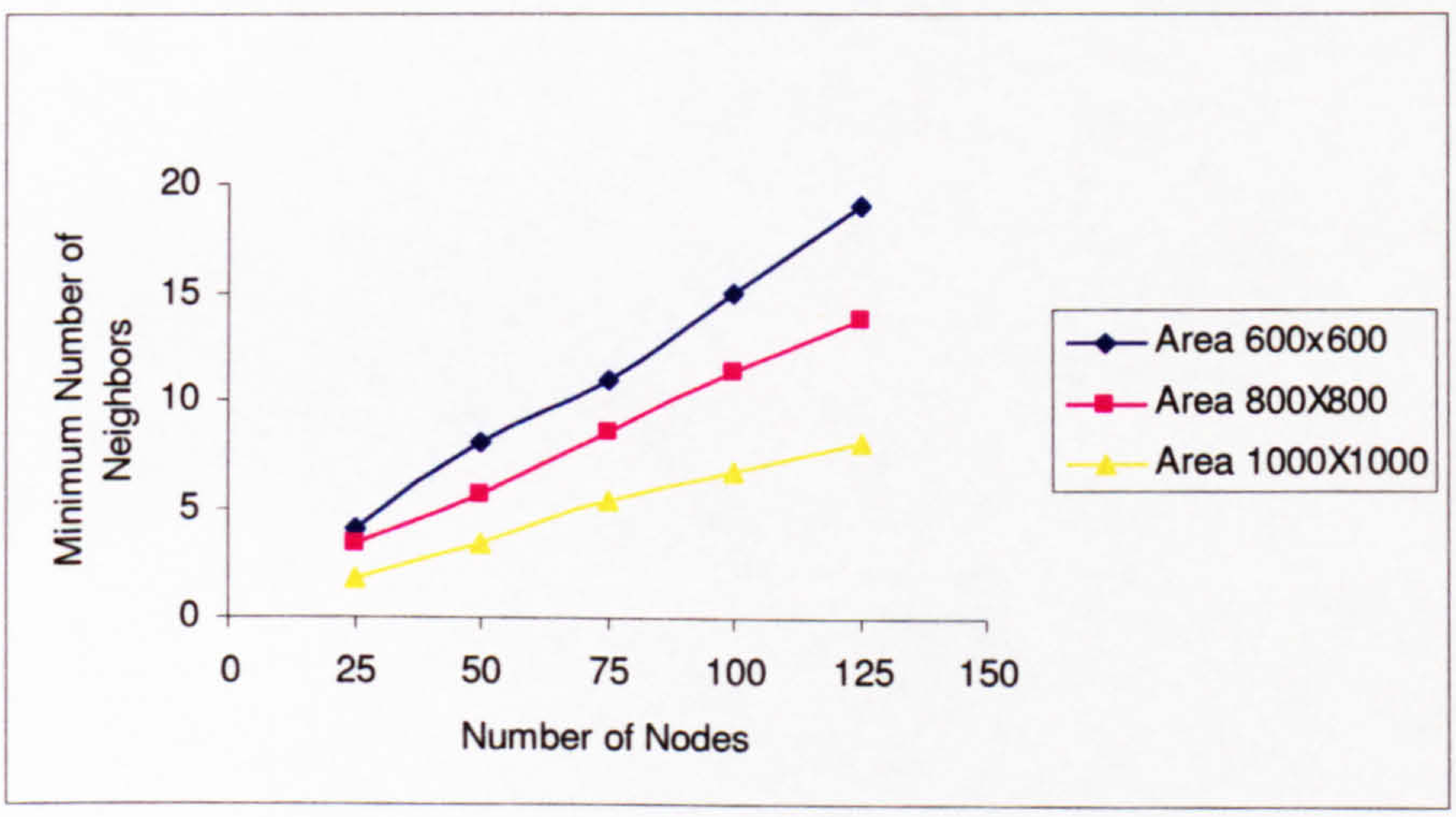

Figure 4.1: Minimum numbers of neighbours (averaged over the whole network) vs. network size with a node speed of 2 m/s.

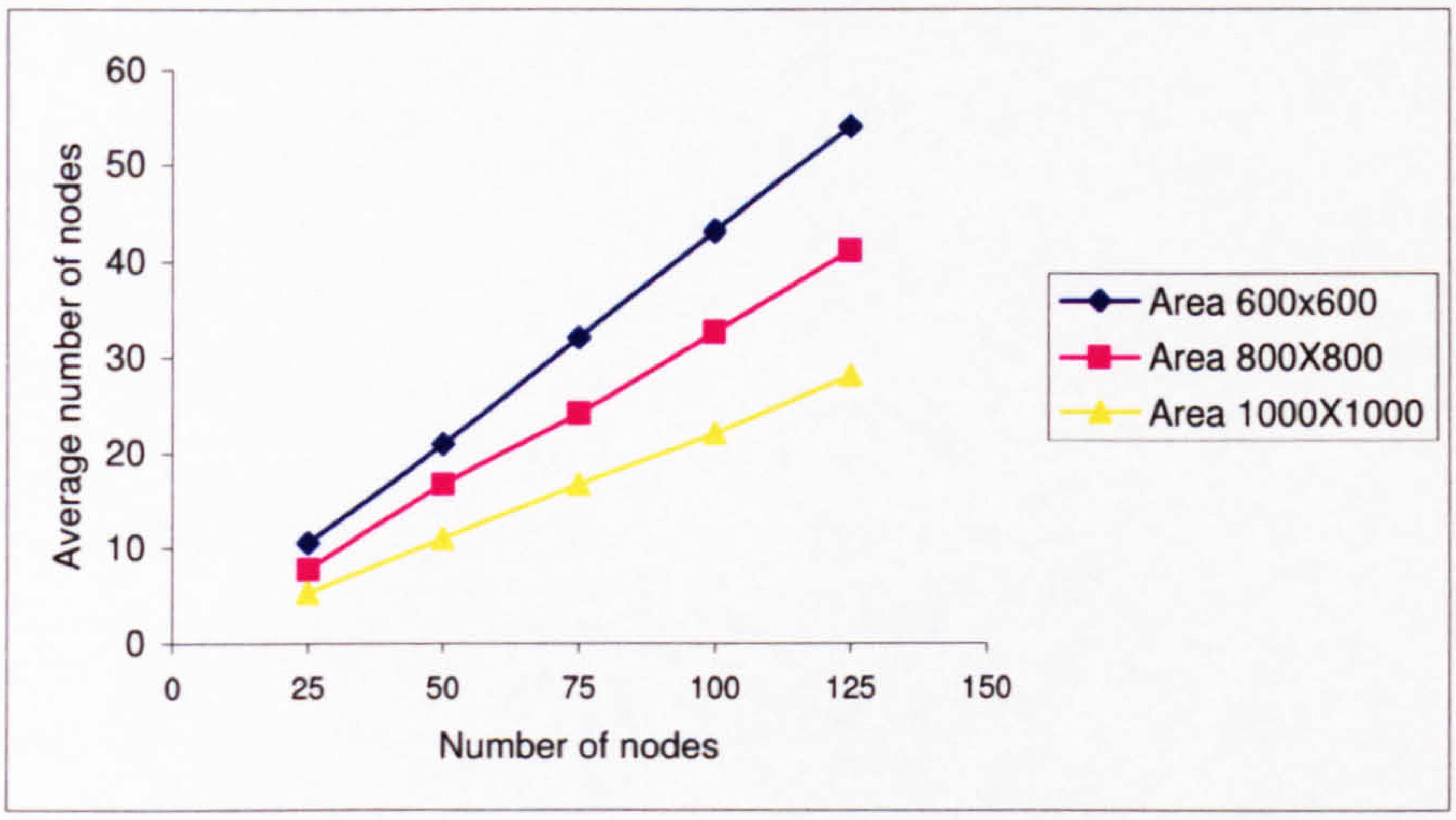

Figure 4.2: Average number of neighbours (averaged over the whole network) vs. network size with a node speed of 2 m/s.

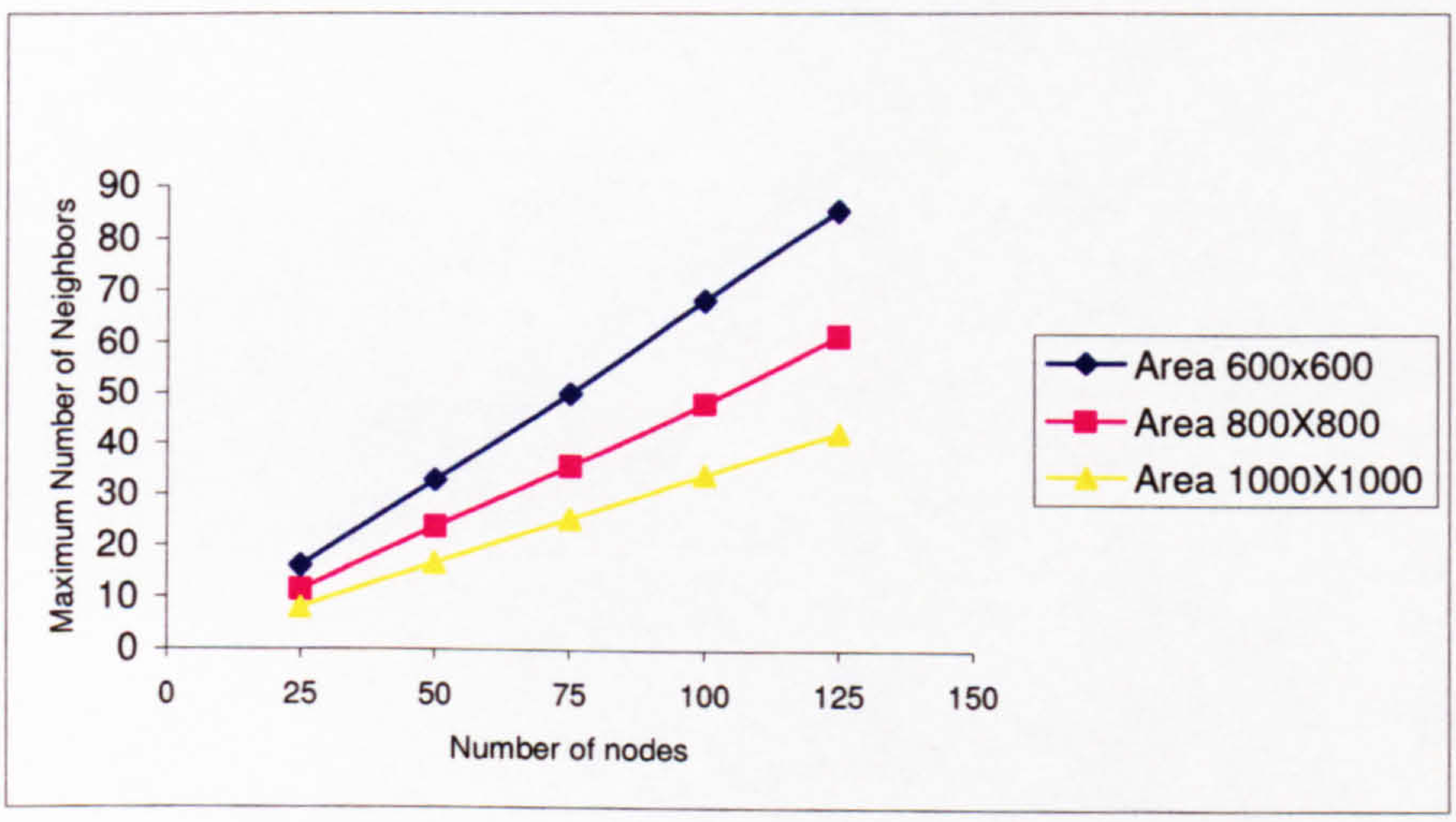

Figure 4.3: Maximum number of neighbours (averaged over the whole network) vs. network size with a node speed of 2 m/s.

Table 4.2: Summary of the minimum, average and maximum number of neighbours of given node (averaged over the whole network)

No. of nodes	Average minimum number of neighbours (average ± std)	Average number of neighbours (average ± std)	Average maximum number of neighbours (average ± std)
25	2 ± 0.03	5.2 ± 0.40	7.9 ± 0.5
50	4 ± 0.05	11 ± 0.9	16.6 ± 1.2
75	5.4 ± 0.07	16.7 ± 1.1	25.34 ± 1.4
100	6.7 ± 0.08	22 ± 1.3	34 ± 1.6
125	8 ± 0.09	28 ± 1.68	42 ± 1.8
150	10± 0.91	34± 1.4	49± 1.9

Table 4.3: Summary of the confidence intervals and margin of errors of minimum, average and maximum number of neighbours of given node (averaged over the whole network)

No. of nodes	95% confidence interval for minimum number of neighbours & relative errors		95% confidence interval for average number of neighbours & relative errors		95% confidence interval for maximum number of neighbours & relative errors	
25	[1.98-2.01]	0.005	[5.16-5.23]	0.01	[7.72-8.07]	0.023
50	[3.98-4.07]	0.004	[10.67-11.32]	0.03	[16.17-17.02]	0.026
75	[5.37-5.42]	0.005	[16.30-17.09]	0.02	[24.84-25.84]	0.020
100	[6.57-6.62]	0.004	[21.53-22.46]	0.02	[33.42-34.57]	0.017
125	[7.96-8.08]	0.004	[27.40-28.60]	0.02	[41.35-42.64]	0.015
150	[9.67-10.32]	0.033	[33.50-34.50]	0.01	[48.32-49.67]	0.014

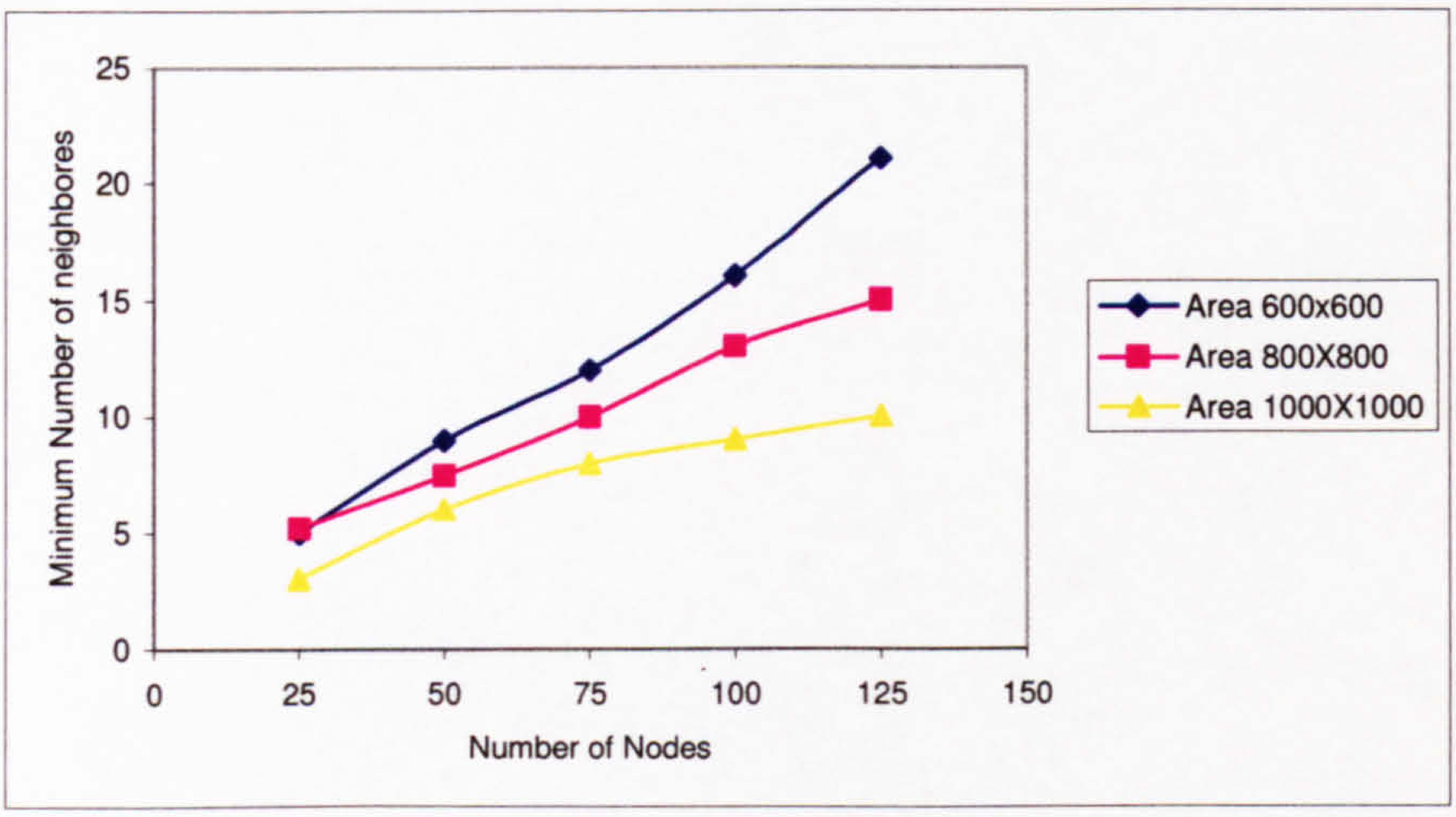

Figure 4.4: Minimum numbers of neighbours (averaged over the whole network) vs. network size with a node speed of 20 m/s

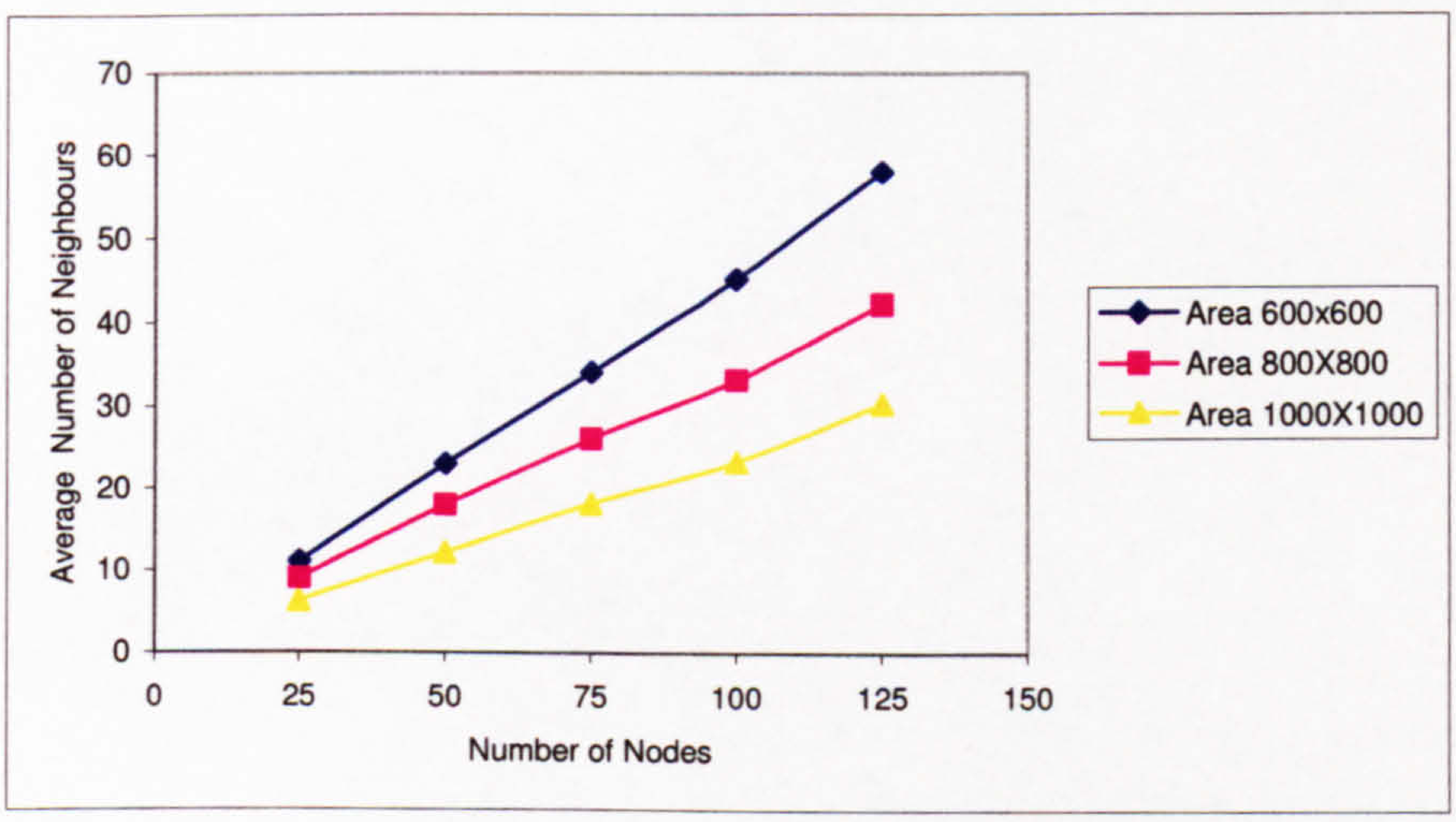

Figure 4.5: Average number of neighbours (averaged over the whole network) vs. network size with a node speed of 20 m/s

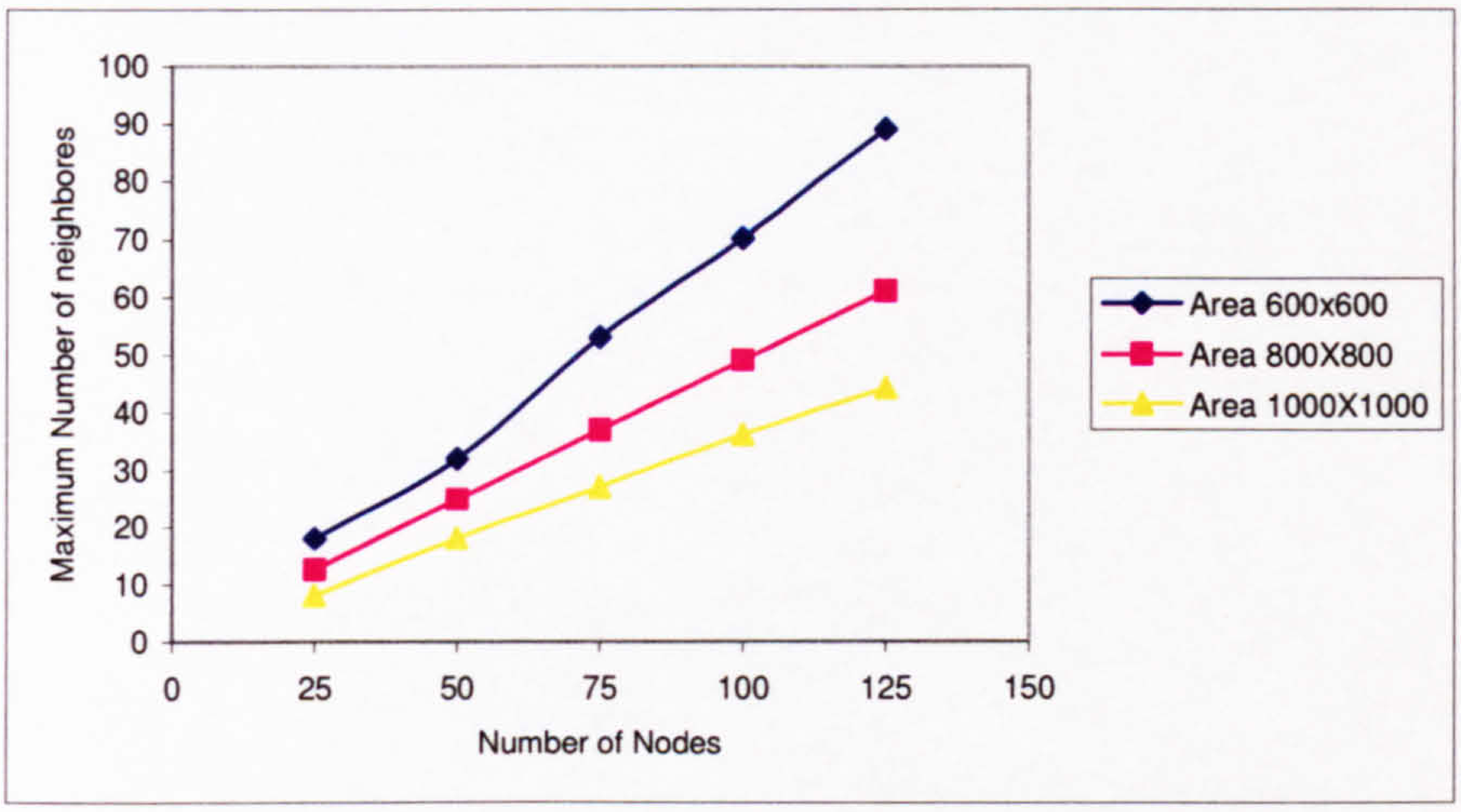

Figure 4.6: Maximum number of neighbours (averaged over the whole network) vs. network size with a node speed of 20 m/s.

4.4 Conclusions

In MANETs, due to node mobility, neighbourhood relationship changes frequently. In order to cope with mobility and have up-to-date neighbourhood information, nodes advertise 'Hello' packets periodically. In this chapter, we have conducted a set of simulation experiments in order to characterise node neighbourhood in MANETs using 'Hello' packet exchange.

In the next two chapters, we will show how neighbourhood information, that includes the minimum, average, maximum number of neighbours of a given node, could be used to devise a new class of efficient probabilistic flooding algorithms for MANETs. These algorithms enable a given node to dynamically adjust its rebroadcast probability depending on whether it is located in a sparse or a dense network region.

Chapter 5

A New Adjusted Probabilistic Flooding Algorithm

5.1 Introduction

In this chapter, we introduce a new probabilistic algorithm that can dynamically adjust the rebroadcasting probability as per the node's neighbourhood distribution using one-hop neighbourhood information. This is based on locally available information and without requiring any assistance of distance devices. The information on one-hop neighbours, collected by means of exchanging short 'Hello' packets, is used to adjust the probability at a given node. If the number of neighbours is high, implying that the node is located in a dense area, it could potentially receive a large amount of rebroadcasts from its neighbours. To avoid such a situation, the rebroadcast probability of the node is set low. Otherwise, the rebroadcast probability is set high when a node is located in a sparse area so that a broadcast packet could reach all nodes in the area.

The use of 'Hello' packets to gather neighbourhood information, of course, introduces extra communication overhead. However, such packets are already used for important operations in MANETs [1, 4, 6, 11, 16, 19, 21, 22, 24, 27, 29, 35, 36, 41, 75, 77, 82, 88, 89, 94]. For instance, popular MANETS routing protocols, like AODV [36] and OLSR [41], already employ 'Hello' packets to exchange information among neighbouring nodes that could be useful for optimising the process of route discovery and maintenance; e.g., see Chapter 4 for further discussion on 'Hello' packets. In this chapter, we show how the availability of 'Hello' packets could be exploited to devise an efficient probabilistic flooding scheme for MANETs. We evaluate the performance of our suggested algorithm, referred to below as adjusted probabilistic flooding, by comparing it against the existing blind flooding as well as fixed probabilistic approaches in terms of the widely used metrics, namely saved rebroadcast and reachability. Simulation results will reveal that the new algorithm exhibits superior performance characteristics with its performance advantages being more noticeable in dense networks, in particular.

The remaining part of this chapter is organised as follows. Section 5.2 describes in detail the adjusted probabilistic flooding algorithm. Section 5.3 discusses the ns-2 simulation model developed in order to evaluate the performance of the new broadcast protocol and then compare it against that of the blind flooding and fixed probabilistic algorithms. Finally, Section 5.4 draws some conclusions from this study.

5.2 Adjusted Probabilistic Flooding

Examining the literature reported on MANETs [14, 20, 25, 29, 33, 40] has revealed that most existing probabilistic protocols introduce uncertainty in the decision making of whether or not a node should perform a rebroadcast. Moreover, the results presented in Chapter 3 have revealed that most of the important system parameters considered in our performance analysis, e.g. node mobility, traffic load, and density have an impact on network performance. In MANETs, where the topology changes frequently, the rebroadcast probability at each node must be dynamically adjusted to account for a given node's surroundings in order to achieve a high saved rebroadcast and high reachability. As a simple rule, the rebroadcast probability should be set high for nodes located in sparse areas and low for nodes located in dense areas.

A straightforward method for estimating network density involves the periodic exchange of 'Hello' packets between neighbours to construct a 1-hop neighbour list at each node. A high (low) a number of neighbours implies that the node is in a dense (sparse) area. We propose a simple scheme which increases the rebroadcast probability if the number of neighbours is low, which indirectly causes the probability at neighbouring nodes to be increased. In a similar fashion, the rebroadcast probability decreases if the number of neighbours is high. This adaptation causes a dynamic stability between rebroadcast probabilities and the number of neighbours among the nodes.

A brief outline of the new adjusted probabilistic flooding algorithm is presented in Figure 5.1. The main operations of the algorithm are as follows. On hearing a broadcast packet *m* at node *X*, the node rebroadcasts the packet according to a high probability, say p_1, if the packet is received for the first time, and the number of neighbours of node *X* is less than the average number of neighbours, $\overline{n}$, which is typical of its surrounding environment. Hence, if node *X* has a low degree (in terms of the number of neighbours), retransmission should be likely. Otherwise, if the number of neighbours of X is greater than the average number of neighbours (i.e., X has a high degree), its rebroadcast probability is set low, say p_2 where $p_1 > p_2$.

The Adjusted Probabilistic Flooding Algorithm

On hearing a broadcast packet m at node X
Get the Broadcast ID from the packet; $\bar{n}$ *average number of neighbour (threshold value);*
Get degree n of a node X (number of neighbours of node X);

If *packet m received for the first time* **then**
    If $n < \bar{n}$ **then**
        Node X has a low degree: the high rebroadcast probability $p = p_1$;
      Else $n \geq \bar{n}$
        Node X has a high degree: the low rebroadcast probability $p = p_2$;
    End if
End if

Generate a random number RN over [0, 1].
If RN $\leq$ *p rebroadcast the received packet; otherwise, drop it*

End algorithm

Figure 5.1: Description of the new adjusted probabilistic flooding algorithm.

In blind flooding, a given node broadcasts a packet to every neighbour which in turn rebroadcasts the received packet to its neighbours that are received for the first time and so on. Therefore, there are (N) possible rebroadcasts, where N is the total number of nodes in the network. In fixed probabilistic flooding, each node decides to rebroadcast or not, according to the same fixed probability p. Since their decisions are independent, the total number of rebroadcasts is Np on the average. In adjusted probabilistic flooding, the rebroadcast probability is dynamically set. In a sparse area, the probability is high, p_1, whereas in a denser area the probability is low, p_2. On the same network topology, the rebroadcast probability p in fixed probabilistic flooding should be no less than the probability of adjusted probabilistic flooding for nodes located in sparse areas in order to maintain the same level of reachability. The number of rebroadcasts in adjusted probabilistic flooding should be lower than that in fixed probabilistic flooding and blind flooding. The number of retransmissions is, on average, $(N_s)p_1 + (N_d)p_2 < (N)p < (N)$ where N_s is the total number of nodes in sparse areas, N_d is the total number of nodes in dense areas and N is the total number of nodes ($N_s \leq N$ and $N_d \leq N$).

For example if N=50 nodes there then are 50 possible rebroadcasts in the blind flooding scheme. Also there are, on average, 35 possible rebroadcasts in fixed probabilistic when the rebroadcast probability p=0.7 (the choice of this probability value will be discussed below). Moreover, the simulations conducted in Chapter 4 have revealed a typical value for a sparse region in a network size of 50 nodes contains Ns =10 nodes while a dense region contains Nd =40 nodes. As a consequence, there are, on average, 21 rebroadcasts in adjusted probabilistic flooding when the rebroadcast probability, for example, p_1=0.7 and p_2=0.35. So in adjusted probabilistic flooding, there are 29 saved rebroadcasts compared to blind flooding scheme which represents 58% of the total rebroadcasts by the blind flooding scheme. Furthermore, there are 14 saved rebroadcasts compared to fixed probabilistic flooding scheme, which represents 28% of the total rebroadcasts by the fixed probabilistic flooding scheme.

5.3 Performance Evaluation

This section presents a performance evaluation of the three broadcast algorithms, notably adjusted probability, fixed probability, and blind flooding in dynamic MANET topologies.

But before doing so, let us briefly discuss the simulation parameters.

Simulation Setup:

We have used the ns-2 packet level simulator (v.2.27) [5] to develop the simulation models for the three algorithms. In our simulations, one node is selected as the data source. A CBR traffic generator is attached to the source. We have used a flat square terrain with dimensions set to 1000x1000m with 50 nodes where each node engaging in communication transmitting within a 250m radius and having a bandwidth of 2Mbps. We have used such a network setup to reduce the likelihood of network partitioning occurring during simulation time. The MAC layer protocol is IEEE 802.11 [37, 67, 81]. The radio frequency at the physical layer is 2.4 GHz of the ISM band [81]. Other simulation parameters are shown in table 5.1. It is worth noting that most of the values for the simulation parameters have been widely adopted in the literature [10, 14, 20, 25]. Furthermore, such values have been selected because they make the time and computing resources to the run most of the simulation scenarios manageable.

The random waypoint model has been used to simulate 30 mobility patterns in order to achieve a 95% confidence interval in the collected statistics. In short, the random waypoint model considers nodes that follow a motion-pause recurring mobility pattern [51]. Each node at the beginning of the simulation remains stationary for pause time seconds, then chooses a random destination and starts moving towards it with speed selected from a uniform distribution (0,max_speed]. After it reaches that destination it again stands still for a pause time interval and picks up a new destination and speed. This cycle repeats until the simulation time terminates. The parameters set to reflect mobility ranging from walking (approximately 2 m/s) to vehicular speeds (approximately 20 m/s) with 0 seconds pause time.

Table 5.1: Summary of the parameters used in the simulation experiments.

Parameter	Value
Transmitter range	250 meters
Bandwidth	2Mbps
IFQ Type Queue/DropTail/PriQueue	50 packets
Simulation time	900 seconds
Pause time	0 seconds
packet size	512 bytes
Topology size	1000×1000 m^2
Number of nodes	25, 50, 75, 100
Maximum speed	2, 4, 8, 12, 16, 20 m/s
'Hello' packet size	12 bytes

Saved Rebroadcasts:

It is well known that blind flooding has the best reachability. However, this is achieved at the expenses of excessive redundant re-broadcasting. Therefore, the main goal of the new algorithm is to reduce the number rebroadcasts so as to reduce traffic in the network and thus decreases the probability of channel contention and packet collision while at the same time maintain good reachability levels comparable to that achieved by blind flooding.

A commonly used metric to assess the performance of broadcast algorithms is the number of re-transmissions with respect to the number of nodes in the network [10, 14, 18, 25, 40].

In this work, we use saved rebroadcast, which is a complementary measure as defined below [10, 14, 18, 25, 40]

Saved ReBroadcasts (SRB): Let r be the number of nodes that received the broadcast packet and let t be the number of nodes that actually transmitted the packet. The saved rebroadcast is then defined by $(r - t)/r$.

We have compared the two versions of probabilistic flooding, fixed probability and adjustable probability; the results for blind flooding have been added for the sake of completeness. It has been revealed in Chapter 3 (and also in [14, 20, 25]) that fixed probabilistic flooding yields the best performance when the rebroadcast probability p is around 07. This enables the fixed probability algorithm to maintain a comparable reachability level (over 95%) to that of blind while at the same time improves on saved re-broadcast.

Figure 5.2 explores saved broadcast (SRB) of the fixed probabilistic and adjusted probability algorithms for low mobility conditions of the max. speed of 2 m/s and 0 second pause time. The rebroadcast probabilities (p_1, p_2) in the new algorithm has been set as follows: The probability p_1 for the nodes located in sparse regions has been varied from 0.1 to 1.0 percent with 0.1 percent increment. The probability p_2 for the nodes located in dense regions has been set at $p_2 = p_1/2$. The results reveal that SRB for adjusted probability is higher than fixed probability for all the values of the rebroadcast probability. For example, when p=0.7 for fixed probability, SRB is 30% while it is 48% for adjusted probability when the probability p= (0.7, 0.35). There is a significant difference between the two variants in that the performance advantage of the adjusted probability over fixed probability and blind flooding is around 18% and 48% respectively.

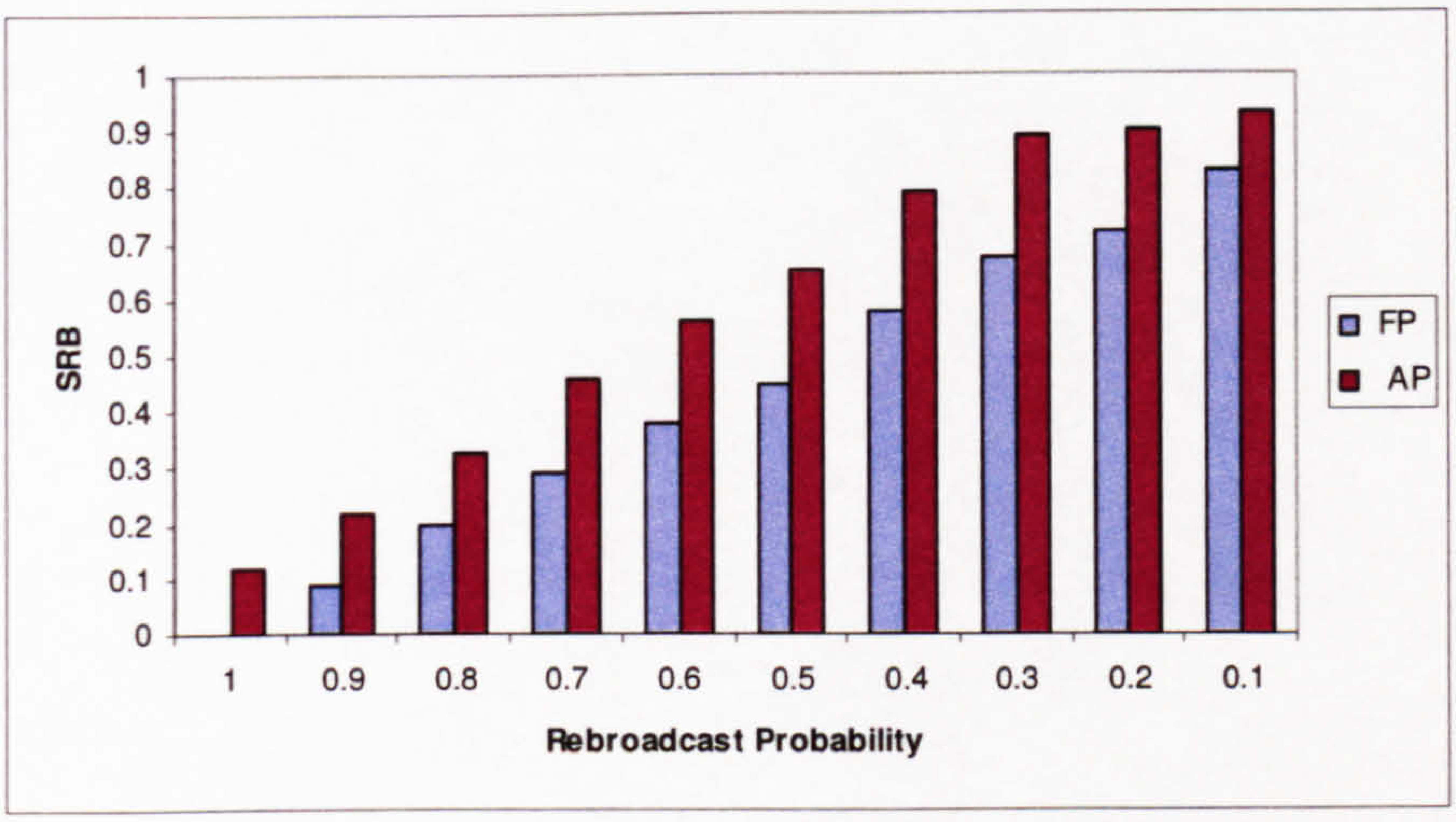

Figure 5.2: SRB vs. rebroadcast probability for a network size of 50 nodes and node speed 2 m/s. FP= fixed probabilistic flooding p_1=0.7.
AP=Adjusted probabilistic flooding $p_2 = p_1/2$.

As will be shown later, after conducting extensive simulations we have realised that our new algorithm manages to achieve a good reachability level (i.e., over 95%) when nodes located in sparse regions have a rebroadcast probability set at around p_1=0.7 while those located in dense regions have a rebroadcast probability set at p_2=0.35. We have also found that when p=0.7 enables the fixed probability scheme to maintain a high reachability. Therefore, these probability values will be adopted for the new algorithm and the fixed probability for the rest of this chapter.

Figure 5.3 explores SRB in the three flooding algorithms for various network mobility conditions (0 second pause time) where the maximum node speed is varied from 2, 4, 10 to 20 m/s for a network with 50 nodes. The performance of adjusted probability decreases to approx. 8 % at 4 m/s and reduces even further to 05 % at very high mobility, 15 and 20 m/s, compared to fixed probability. Also the difference in performance decreases to approx. 40% at 4 m/s and reduces even further to 36 % at very high mobility, 15 and 20 m/s, compared to blind flooding.

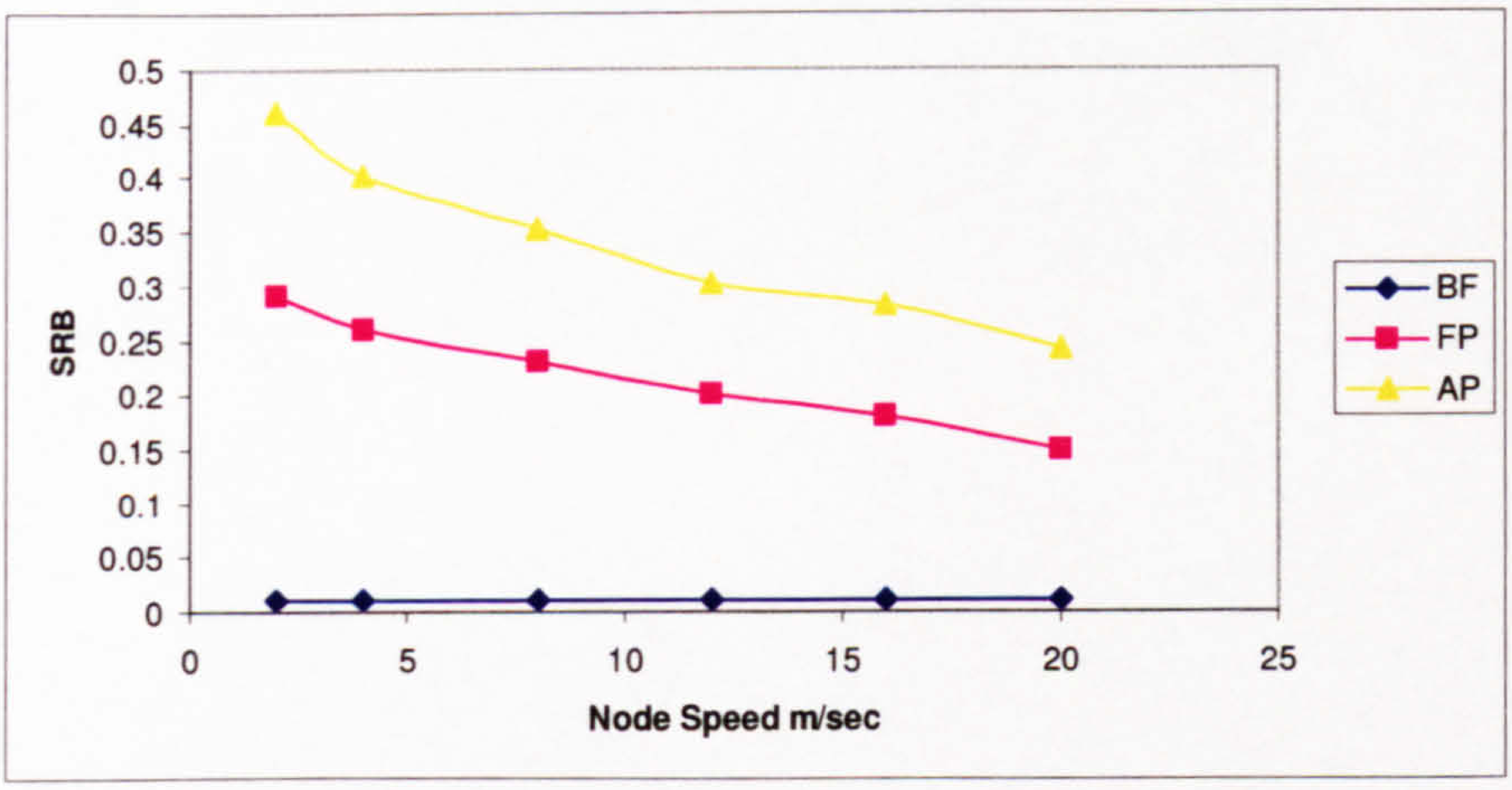

Figure 5.3: SRB vs. node speed 2, 4, 10, 16, 20 m/s for a network size of 50 nodes. BF= Blind flooding.

The next set of results depicts the impact of traffic on network performance. The traffic load is modeled using constant bit rate data stream with the following three relative traffic loads:

- Low Traffic Load: 1 broadcast packet is generated per second;
- Medium Traffic Load: 5 broadcast packets are generated per second;
- Heavy Traffic Load: 10 broadcast packets are generated per second.

Figure 5.4 depicts SRB results where the three traffic loads have been applied to the network where system size is kept at 50 nodes under a low network mobility condition with the maximum speed of 2 m/s and 0 second pause time. Again, our algorithm can significantly improve SRB at different traffic loads compared to fixed probabilistic and blind flooding. SRB increases as the traffic load increases. For instance, SRB increases from 10 % to 16% compared to fixed probability when the traffic load increases from low to high. Furthermore, SRB increases from 35% to 46% compared blind flooding when the traffic load increases from low to high. However SRB starts to decrease when the network is subjected to heavy traffic loads.

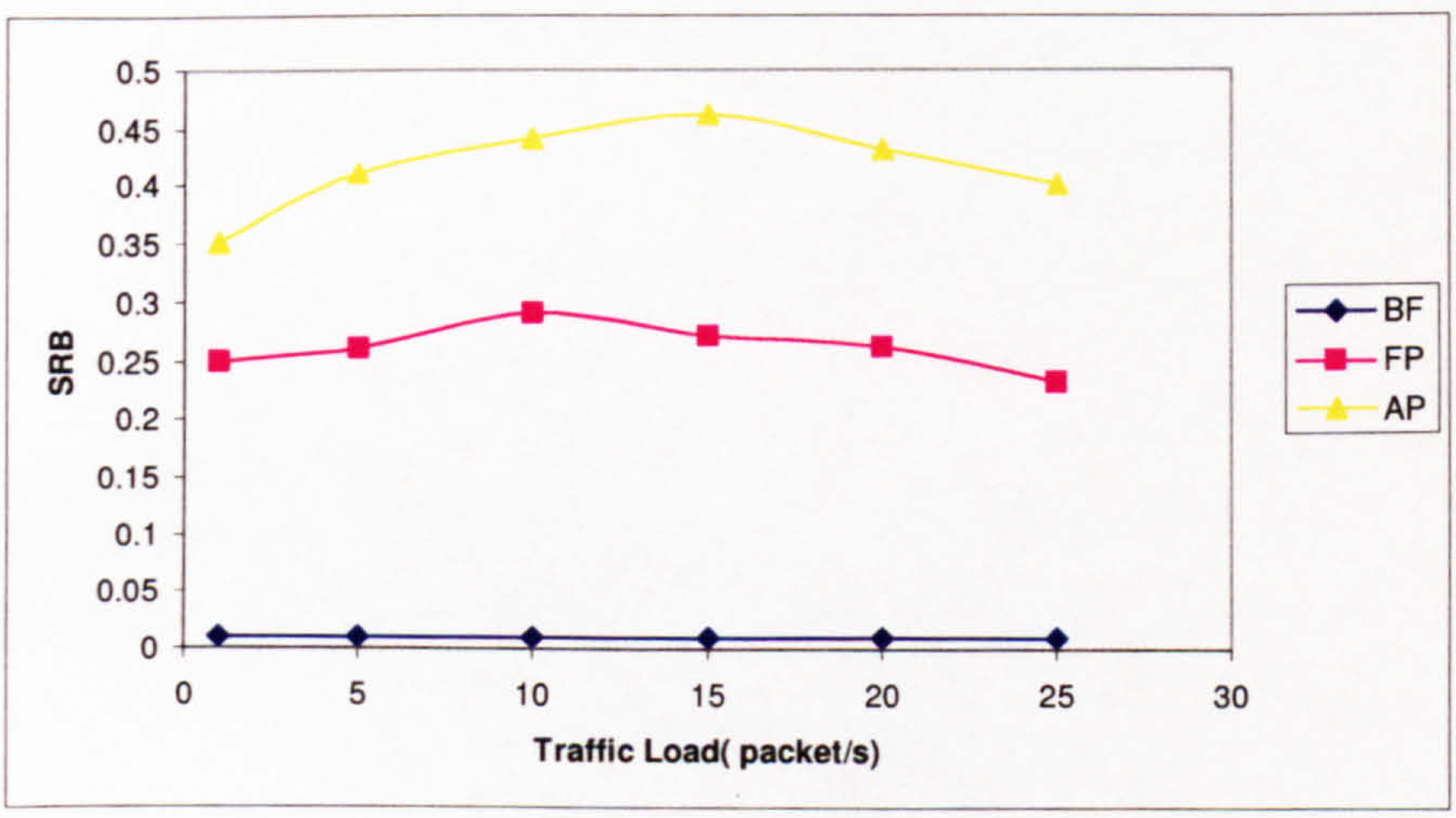

Figure 5.4: SRB vs. network traffic load for a network size of 50 nodes and node speed 2 m/s.

Network density denotes the number of network nodes per unit area for a given transmission range. In order to assess the impact of network density on the three flooding algorithms, we have considered nodes moving continuously at a maximum speed of 2 m/s, with the following three relative levels of network density:

- Low density: 25 nodes;

- Medium density: 50 nodes;

- High density: 100 nodes.

Figure 5.5 explores SRB in three versions of probabilistic flooding for the different network densities. When the broadcast probability is adjusted, SRB is 36% in low density networks and 56% in high density networks compared to fixed probability. Moreover, when the broadcast probability is adjusted SRB is 36% in low density networks and 56% in relatively higher density networks (e.g., 100 nodes) compared to blind flooding. There is a noticeable difference between the three variants in that the performance of the adjusted probability over fixed probability and blind flooding is higher by around 12% and 22%, respectively, in high density networks. The results in Figure 5.5 reveals that few saved rebroadcasts can be saved in sparser networks; our adjusted probabilistic flooding algorithm has more noticeable performance advantage over fixed probabilistic algorithm in dense networks. In blind flooding SRB does not change as the traffic load increase, in probabilistic flooding, SRB increases slightly then decreases after the number of connections is greater than 15. The behaviour of figure 5.4 and figure 5.5 are not this is because in blind flooding every node rebroadcast the broadcast packet and as a result there is no real savings in the number of rebroadcasts performed by the network nodes; every node must retransmit its packet. On the other hand, in probabilistic flooding, some nodes might be prohibited from rebroadcast a packet if its probability value is higher than the set threshold, and hence there is an increase in the number of savings made by nodes in terms of re-broadcasting. However, as traffic increases, this saving decreases because contention increases, and thus packets are lost. As a consequence, nodes have to retransmit their packets

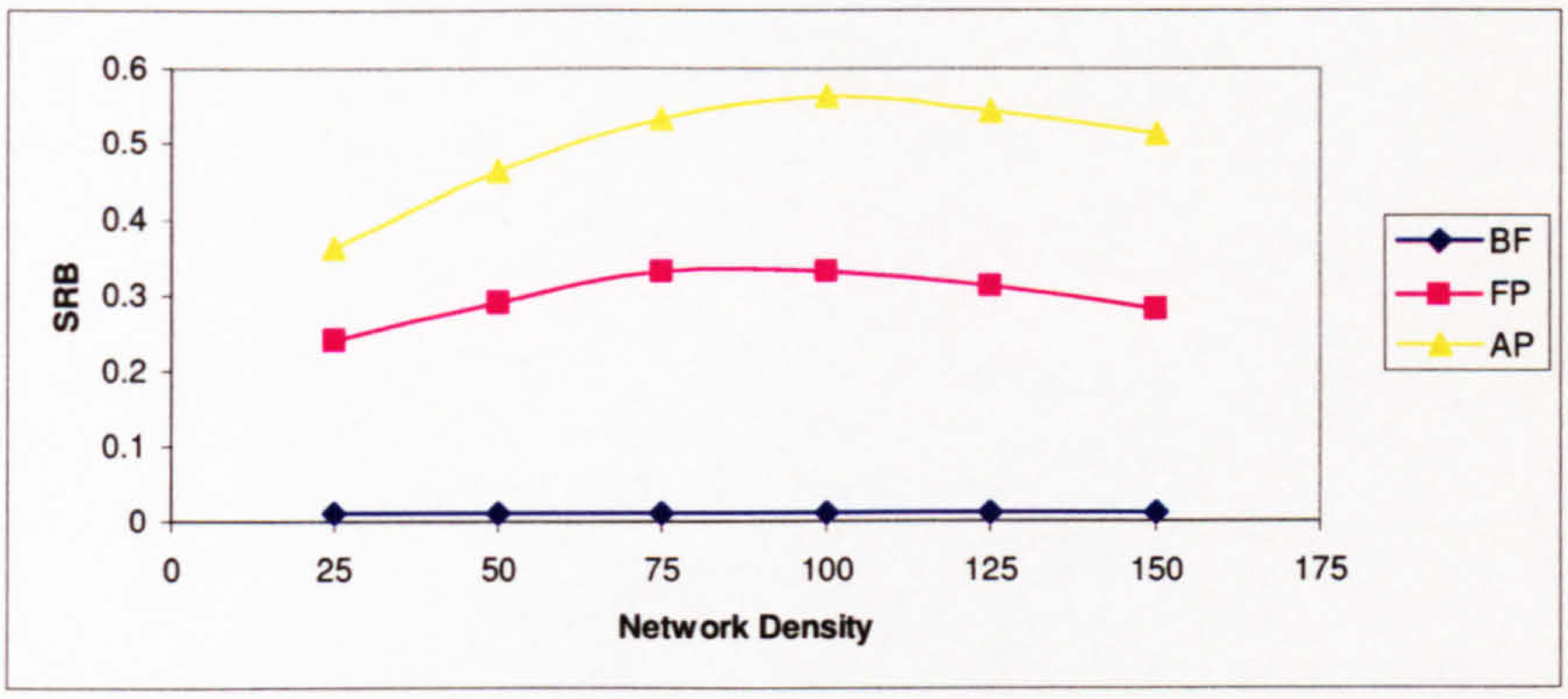

Figure 5.5: SRB vs. network density (with different number of nodes 25, 50, 75, 100) for node speed 2 m/s.

Reachability:

A node may not receive a broadcast packet if all of its neighbours decide to inhibit rebroadcasts. In the absence of network partitioning, the flooding approach guarantees that all nodes can receive the broadcast packets at expense of extra cost caused by redundant rebroadcasts. In reality, however, redundant rebroadcasts also contribute to packet collisions that may eventually cause packet drops, thus adversely affecting the reachability. Depending on the value of the probability, probabilistic approaches may have lower reachability compared to blind flooding. However, by choosing an appropriate probability value, the new adjusted probabilistic flooding could achieve a good degree of reachability comparable to that achieved by blind flooding while it is higher than that achieved by fixed probability. A definition of the reachability metric is given below [10, 14, 18, 25, 40].

Reachability (RE): is the percentage of nodes that receive the broadcast packet to the total number of nodes in the network. For useful information, the total number of nodes should include those nodes that are part of a connected component in the network. For disconnected networks this measure should be applied to each of the components separately [10, 14, 18, 25, 40].

Figure 5.6 explores RE results in fixed probabilistic and adjusted probabilistic flooding for a network with 50 nodes at low mobility conditions (max. speeds of 2 m/s) and 0 pause time. In the new algorithm, the probability p_1 is varied from 0.1 to 1.0 percent with 0.1 percent increment while p_2 has been at $p_1/2$. The figure shows that as the rebroadcasts probability increases RE increases for both fixed probability and adjustable probability. Moreover the figure reveals RE can be over 95% when the rebroadcasts probability is p_1=0.7 and p_2=0.35 for adjusted probability and when the probability is p=0.7 for fixed probability.

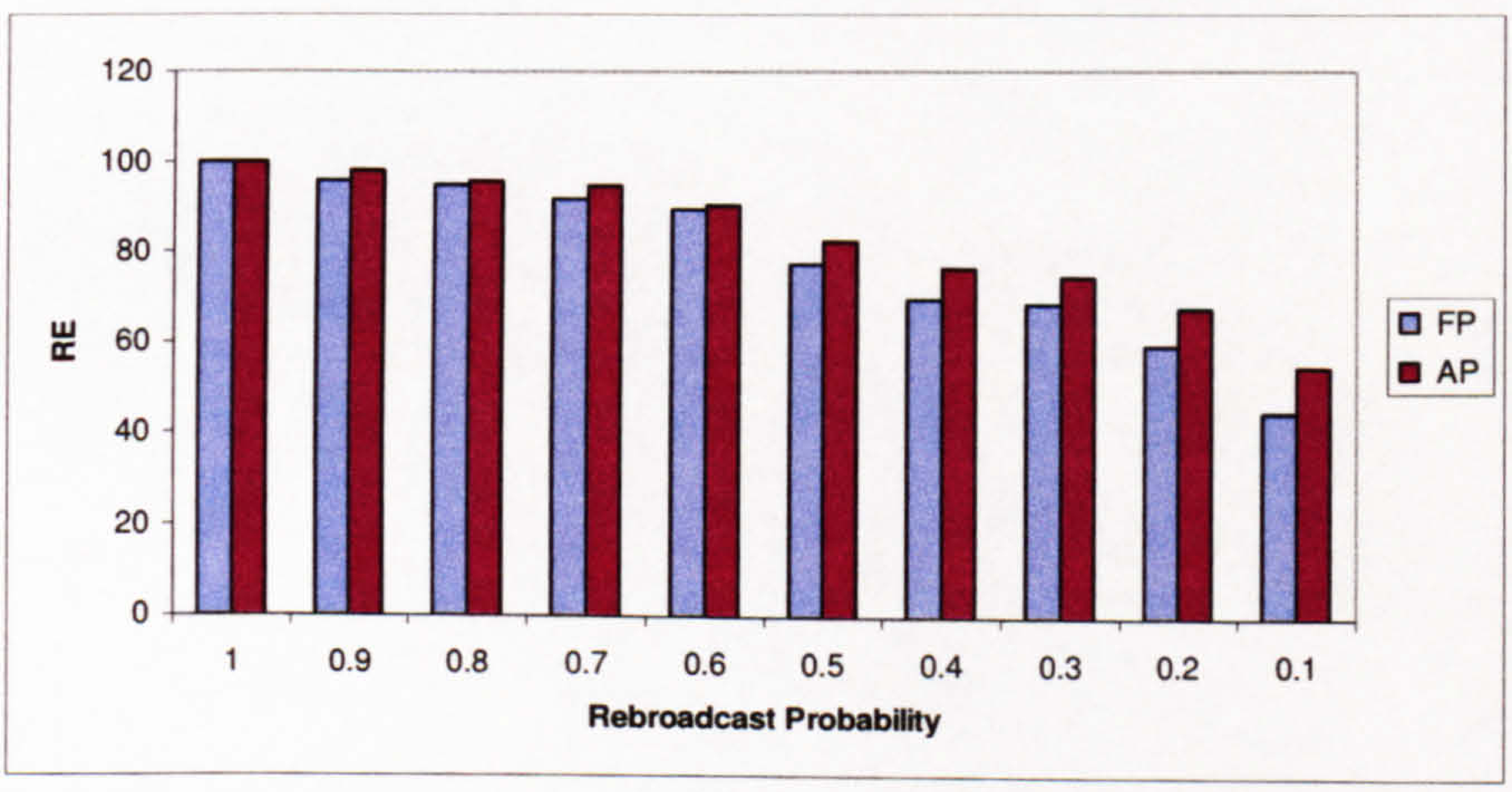

Figure 5.6: RE vs. rebroadcast probability for a network size of 50 nodes and node speed 2 m/s.

Figure 5.7 depicts RE in blind, fixed probabilistic, and adjusted probability flooding algorithms p= (0.7, 0.35) for various network mobility conditions (0 second pause time) with the maximum speed of the nodes has been varied from 2, 4, 10 to 20 m/s for a network with 50 nodes. RE improves when the nodes move with a faster speed.

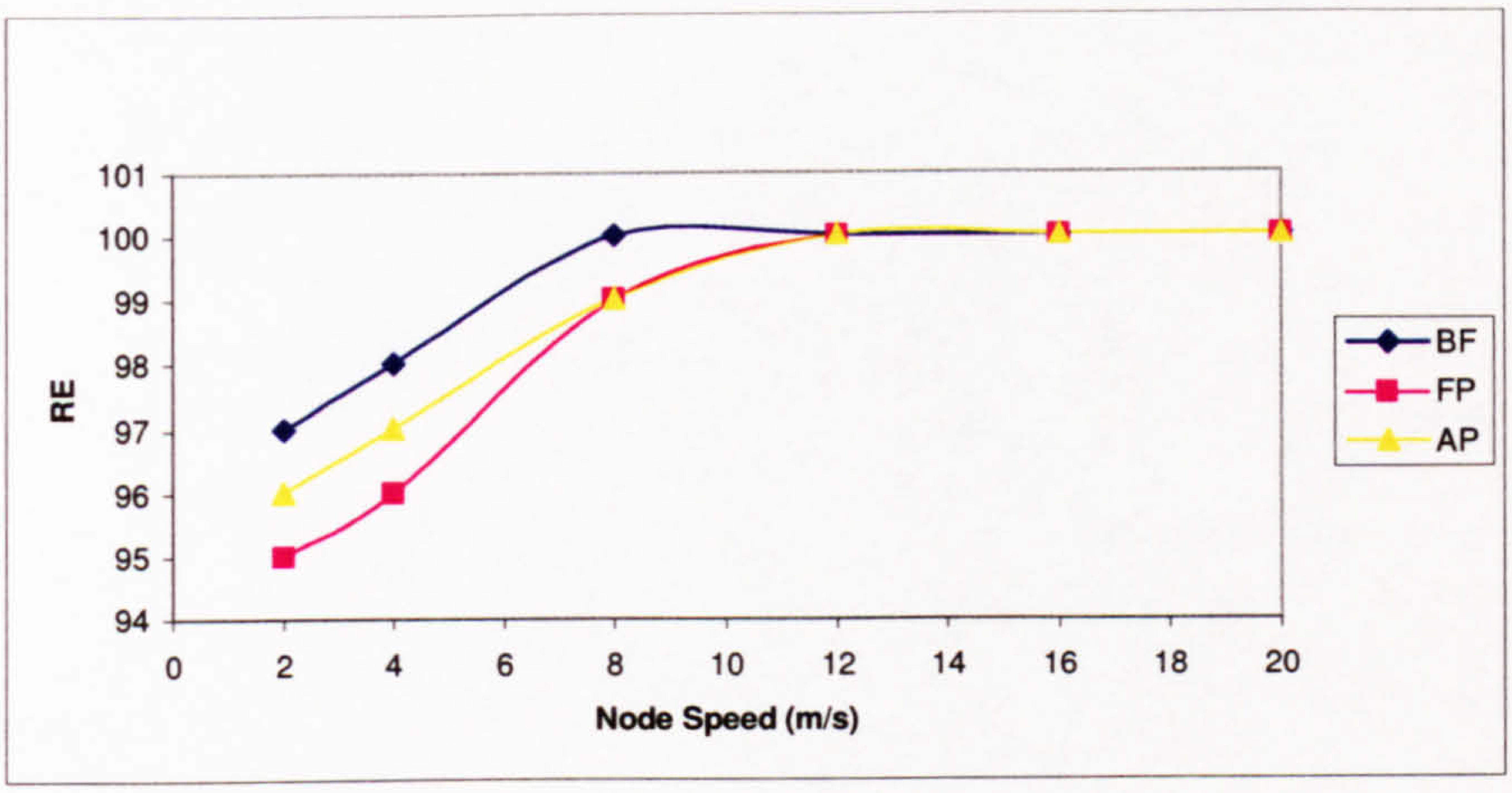

Figure 5.7: RE vs. node speed 2, 4, 10, 16, 20 m/s for a network size of 50 nodes.

Figure 5.8 shows RE results where the three traffic loads have been used. The network size is kept at 50 under low network mobility conditions (0 second pause time) with the maximum speed of 2 m/s. Again, our algorithm can significantly improve RE at different traffic loads compared to fixed probability and blind flooding. RE increases as the traffic load increases. For instance, RE reached 100% when the traffic load is low (i.e. 5 packets/s) and is comparable to that in fixed probability when the traffic load increases. However, RE start decreases at the traffic load of10 packets/s and even more when heavier traffic load is injected into the network.

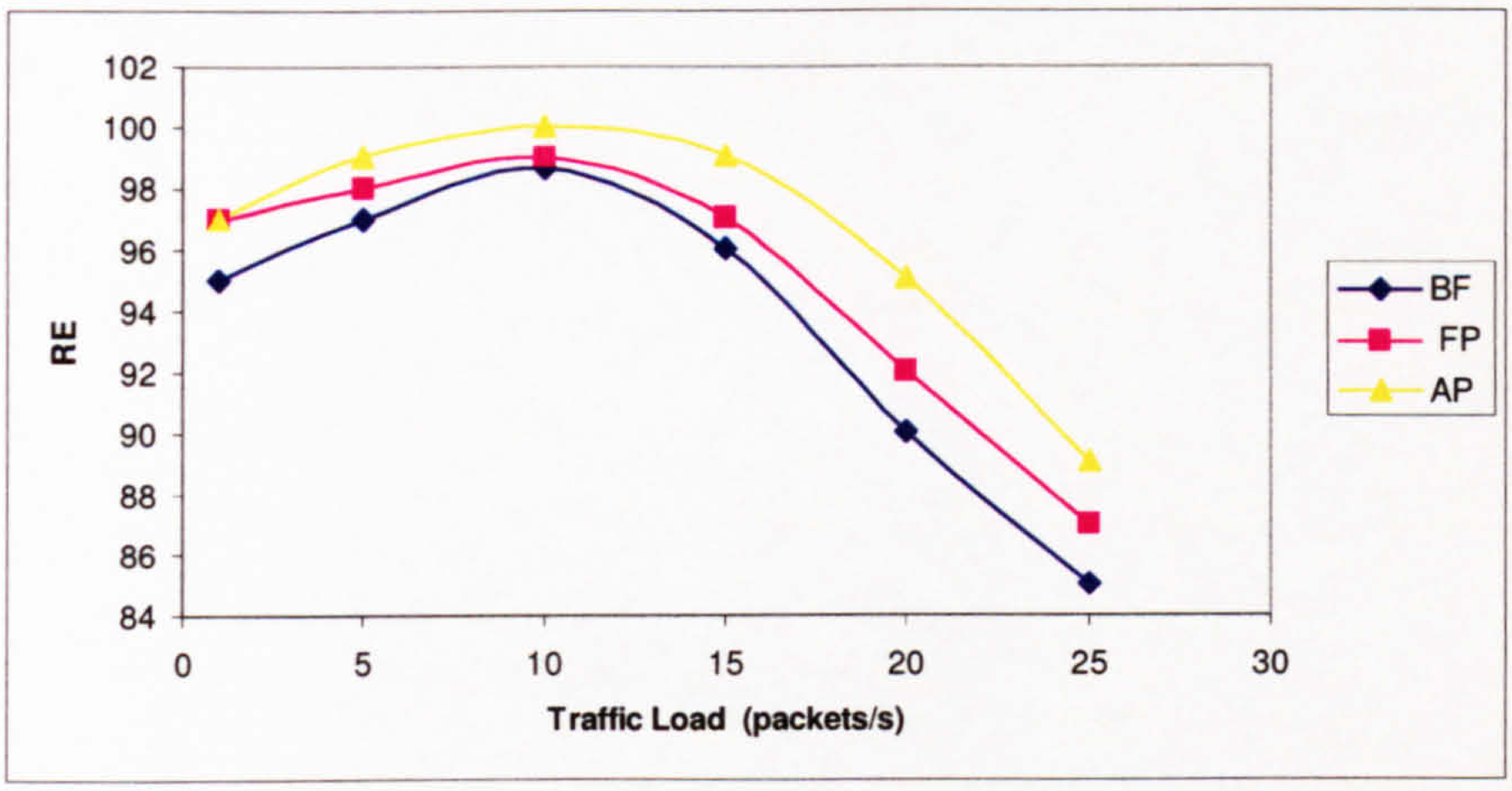

Figure 5.8: RE vs. network traffic load for a network size of 50 nodes and node speed 2 m/s.

Figure 5.9 shows that RE increases when network density increases, regardless of what type of flooding algorithm is used. Blind flooding has the best performance in that reachability is almost 100%. The performance of adjusted probability shows that RE is above 95% for any network density. For all network densities, RE in our algorithm is the same or better than in the fixed probabilistic scheme when the probability in the latter is assigned to 0.7. In relatively higher density networks, i.e., 100 nodes and above, RE in the adjusted probabilistic approach is comparable to that of flooding; reachability is close to 100%.

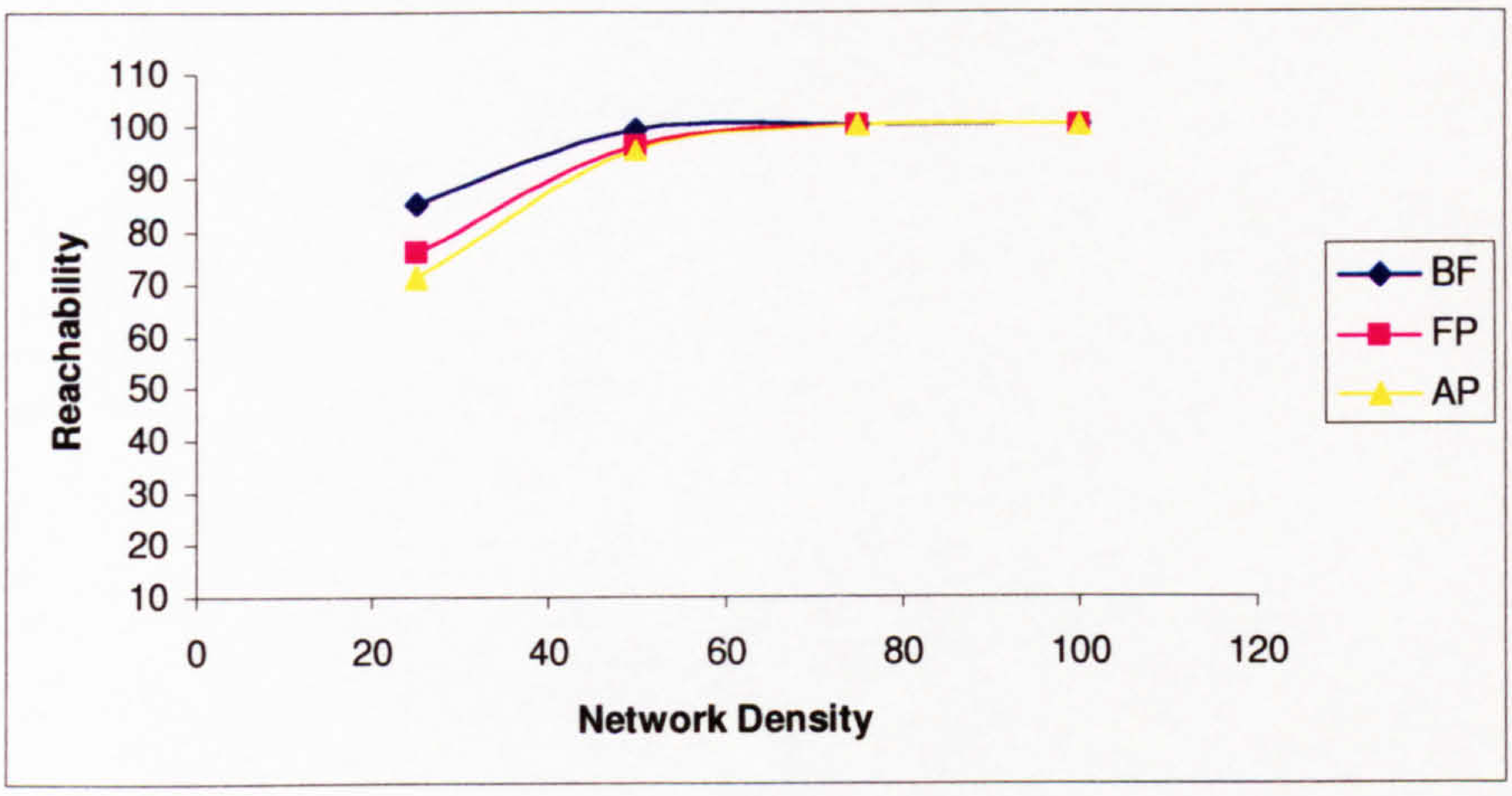

Figure 5.9: RE vs. network density (with different number of nodes 25, 50, 75, 100) for node speed 2 m/s.

'Hello' Packets:

'Hello' packets are periodically generated by a given node in order to know the number of its neighbours. These are extra control packets sent by nodes to successfully accomplish broadcast operations. Each node sends a short packet that informs its neighbours of its presence. So a node can know its neighbours by simply listening to the medium. Since nodes obtain neighbourhood information through 'Hello' packets, the information in the 'Hello' packet varies depending on it usage. Thus it is necessary to quantitatively assess the impact of the size of the 'Hello' packets on the overhead involved and thus be able to comment on any possible performance tradeoffs. To this end, we have used a 'Hello' packet with a size of 12 bytes for exchanging neighbourhood information. The 'Hello' packet is sent every second as recommended in the AODV protocol [36]. For the sake of the present discussion, let us assume the following system parameters.

Channel bandwidth=2Mbps;

Number of nodes=50 nodes;

Broadcast traffic rate=1 packet/s;

Broadcast packet size =512 bytes;

Hello packet size=12 bytes;

The rates (in kbps) of the broadcast and 'Hello' packets are:

$$Packet\_Rate = (512\times8\times1)/1024 = 4 \text{ kbps} \quad (1)$$

$$Hello\_Packet\_Rate = (12\times8\times1)/1024 = 0.09 \text{ kbps} \quad (2)$$

In blind flooding, there are (N-1) rebroadcasts, where N is the total number of nodes. So the total packet rate is given by

$$Total\_Packet\_Rate(Blind\_Flooding) = Packet\_Rate + Packet\_Rate\times(N) \quad (3)$$

$$= 4 + 4\times50 = 204 \text{ kbps}$$

Let the rebroadcast probability be p=0.7 in fixed probabilistic flooding. The total number of rebroadcasts is on average (N-1)$\times p$. So, the total packet rate can be written as

$$Total\_Packet\_Rate(Fixed\_Probability) = Packet\_Rate + Packe\_Rate\ (N)\times p \quad (4)$$

$$= 4+4\times 50\times0.7 = 144 \text{ kbps}$$

Let the rebroadcast probability be p_1=0.7 and p_2=0.35 in adjusted probabilistic flooding. As discussed above, for a network size of N=50 nodes, a sparse region contains N_s =10 nodes and a dense region contains Nd = 40 nodes. The total packet rate in adjusted probabilistic flooding is found to be

$Total\_Packet\_Rate(Adjusted\_Probability) = Packet\ rate + Packet\_Rate \times (N_s p_1 + N_d p_2)$

$= 4+4\times(10\times0.7)+4\times(40\times0.35) =$ 88 kbps (5)

The total packet rate in the adjusted probabilistic flooding is lower than in blind flooding by the following amount

$Saved\_Total\_Packet\_Rate = Total\_Packet\_Rate(Blind\_Flooding) -$

$Total\_Packet\_Rate(Adjusted\_Probability) =$ 204-88 =116 kbps (6)

Similarly, the total packet rate in the adjusted probabilistic flooding is lower than in blind flooding by the following amount

$Saved\_Total\_Packet\_Rate = Total\_Packet\_Rate(Fixed\_Probability) -$

$Total\_Packet\_Rate(Adjusted\_Probability) =$ 144-88 =56 kbps (7)

The above analysis is certainly simple and straightforward. Nonetheless, we can use it to fairly conclude that with a relatively low 'Hello' packet rate of 0.09 kbps, the new adjusted probabilities flooding algorithm could save up to 116 kbps in broadcast packets compared to blind flooding and up to 56 kbps compared to the fixed probability algorithm. The performance advantage of adjusted probabilistic flooding is more noticeable if the size or the traffic rate of the broadcast packets is further increased.

5.4. Conclusions

This chapter has described a new adjusted probabilistic flooding algorithm for MANETs where the rebroadcast probability is set by considering nodes' density regions. In order to improve performance in terms of saved rebroadcasts while keeping a reachability level comparable to that achieved by blind flooding, in the new algorithm the rebroadcast probability of nodes situated in low density regions is set higher than that of nodes situated in higher density regions.

Compared against the blind flooding and fixed probabilistic flooding schemes, the simulation results presented above have revealed that the new algorithm can improve without scanting reachability the saved broadcast up to 26% compared to fixed probabilistic flooding and 56% compared to blind flooding, even under conditions of high mobility and high density. A similar improvement can also be obtained when various traffic loads are applied to the network.

This chapter has demonstrated that assigning two different forwarding probabilities to network nodes depending on their density regions help to reduce the number of rebroadcasts, and as a consequence help to reduce network traffic and decrease the probability of channel contention and packet collision. As a natural extension of this research, it would be interesting to assess whether refining further the rebroadcast probability using more refined levels for nodes' density regions leads to further improvement in the performance of probabilistic flooding. To this end, the next chapter will introduce and evaluate the performance of another new probabilistic algorithm that uses more than two different re-broadcast probabilities at a given network node.

Chapter 6

A New Highly Adjusted Probabilistic Flooding Algorithm

6.1 Introduction

Chapter 5 has revealed that assigning two different forwarding probabilities to network nodes depending on their density regions helps to reduce the number of rebroadcasts, and as a consequence improves saved rebroadcasts while maintains a good reachability level. This chapter proposes a new highly adjusted probabilistic flooding algorithm that can dynamically adjust the rebroadcasting probability at a given node according to its neighbourhood density. The algorithm is based on the same approach as that introduced in the previous chapter. However, the forwarding probability is further refined in that three different forwarding probabilities (as opposed two probabilities) are assigned to network nodes in the new algorithm discussed in this chapter.

When a broadcast packet reaches a node for the first time, it is rebroadcast according to a probability which depends on the node's degree i.e. number of neighbours. The packet is re-broadcast with probability p_1 if the node is inside a sparse area. Alternatively, it is re-broadcast with probability p_2 ($p_2 < p_1$) if the degree denotes a medium density area. Finally, the node rebroadcasts the packet with a lower probability p_3 ($p_3 < p_2 < p_1$) if it is located in a dense area. Sparse, medium and dense areas correspond to the degree threshold values which have been determined through simulations which have been discussed in Chapter 4.

As in adjusted probabilistic flooding, short 'Hello' packets are used in the new highly adjusted flooding algorithm in order to gather information on one-hop neighbours to update the current number of neighbours of a given node. The analysis conducted in Chapter 5 has revealed that the added cost by introducing 'Hello' packets is small compared to the achieved reduction in the number of redundant rebroadcasts. In this chapter, we will describe the operation of highly adjusted flooding and evaluate its performance against the existing fixed probabilistic as well as adjusted probabilistic flooding. Simulation results will reveal that the new algorithm exhibits superior performance characteristics over the other schemes, with its performance advantages being more noticeable in dense networks, in particular.

The remaining part of this chapter is organised as follows. Section 6.2 describes the highly adjusted probabilistic flooding algorithm. Section 6.3 compares its performance against the fixed probabilistic and adjusted probabilistic flooding algorithms. Finally, Section 6.4 concludes the chapter.

6.2 Highly Adjusted Probabilistic Flooding

On hearing a broadcast packet *m* at node *X*, the node rebroadcasts the packet according to a high probability, say p_1, if the packet is received for the first time, and the number of neighbours of node *X* is less than the minimum numbers of neighbours, n_1. Alternatively, if the number of neighbours of the node *X* is greater or equal the minimum number of neighbours, n_1, and the number of neighbours less than or equal the maximum numbers of neighbours, n_2, *X* has a medium degree and the rebroadcast probability is set at p_2 ($p_2 < p_1$). Otherwise, if the number of neighbours of the node *X* is greater than maximum number of neighbours, n_2, then the rebroadcast probability is set low, p_3, where $p_3 < p_2 < p_1$. A brief outline of the new algorithm is presented in Figure 6.1.

The Highly Adjusted Probability for Probabilistic Broadcasting Algorithm

On hearing a broadcast packet m at node X:
Get the Broadcast ID from the packet; n_1 *minimum numbers of neighbour,* n_2 *maximum number of neighbour and* $\bar{n}$ *average number of neighbour all are threshold values;*
Get degree n *of a node X (number of neighbours of node X);*

If packet m received for the first time then
    If $n < n_1$ ***then***
        Node X has a low degree: the high rebroadcast probability $p = p_1$;
      Else If $n \geq n_1$ ***and*** $n \leq n_2$ ***then***
        Node X has a medium degree: the medium rebroadcast probability $p = p_2$;
      Else If $n > n_2$ ***then***
        Node X has a high degree: the low rebroadcast probability $p = p_3$;
    End if
End if
Generate a random number RN over [0, 1].
If RN $\leq$ *p rebroadcast the received packet; otherwise, drop it*

End algorithm

Figure 6.1: A description of the new highly adjusted probabilistic flooding algorithm.

Following the same argument presented in Chapter 5 shows that in highly adjusted flooding, the number of rebroadcasts is, on average, $(N_s)p_1 + (N_a)p_2 + (N_d)p_3$ where N_s is the number of nodes in sparse regions, N_a is the number of nodes in medium regions, N_d is the number of nodes in dense regions. For instance, consider a MANET with N=50 nodes. As discussed in Chapter 5, there are 50 rebroadcasts in blind flooding, 35 rebroadcasts, on average, in fixed probabilistic flooding when p=0.7, and 21 rebroadcasts in adjusted probabilistic flooding when the p_1=0.70 and p_2=0.35.

The simulations conducted in Chapter 4 have revealed that a typical value for a sparse region in a network size of 50 nodes contains N_s =4 nodes while a medium region contains N_a=16 nodes and a dense region contains N_d =30 nodes. As a consequence, there are, on average, 16 rebroadcasts in highly adjusted probabilistic flooding when the rebroadcast probability, for example, is set at p_1=0.7, p_2=0.35 and p_3=0.25, respectively. So in highly adjusted probabilistic flooding, there are 34 saved rebroadcasts compared to blind flooding which represents 68% of the total rebroadcasts by blind flooding. Furthermore, there are 19 saved rebroadcasts compared to fixed probabilistic flooding, which represents 36% of the total rebroadcasts by fixed probabilistic flooding. Finally, there are 5 saved rebroadcasts compared to adjusted probabilistic flooding, which represents 24% of the total rebroadcasts by adjusted probabilistic flooding.

6.3 Performance Evaluation

The network setup discussed in Chapter 5 is used here again. We will briefly describe it here for the sake of completeness. In our simulations, one node is selected as the data source. A CBR traffic generator is attached to the source. A flat square terrain with dimensions set to 1000x1000m containing 50 nodes is used. Each node can engage in communication transmitting within a 250m radius and having a bandwidth of 2Mbps. The MAC layer protocol is IEEE 802.11[37, 67, 81]. The nodes move according to the random waypoint model [51]. This mobility model has been used to simulate 30 topologies in order to achieve a 95% confidence interval in the collected statistics. The maximum speeds of 2, 4 10, 12, 20 m/s and pause time 0 sec have been examined. The other simulation parameters are summarised in Table 6.1.

Table 6.1: Summary of the parameters used in the simulation experiments.

Parameter	Value
Transmitter range	250meters
Bandwidth	2Mbps
IFQ Type Queue/DropTail/PriQueue	50 packets
Simulation time	900 seconds
Pause time	0 seconds
Packet size	512 bytes
Topology size	1000×1000 meter^2
Number of node	25, 50, 75, 100
Maximum speed	2,4,8,12, 20 m/s
Hello packet size	12 bytes

Saved Rebroadcasts (SRB):

In what follows, we will only report the results obtained from simulation experiments for the sake of conciseness. The reader is referred to Chapters 3 and 5 for the interpretation of the performance behaviour exhibited by the algorithms as most of the analysis carried out in those previous chapters is still valid here.

We have compared the saved rebroadcasts (SRB) in the three versions of probabilistic flooding: fixed, adjusted, and highly adjusted. The probabilities in these algorithms have been set in such a way to enable a particular algorithm to yield the best performance levels. The rebroadcast probability for the fixed probabilistic algorithm is set at p=0.7 as revealed in Chapter 3 (and also in [14, 17, 20, 40]). The rebroadcast probability for the adjusted probabilistic algorithm is set at p_1=0.7 and p_2=0.35 for sparse and dense areas, respectively, as revealed in Chapter 5. For the highly adjustable probabilistic algorithm, extensive simulation experiments have been performed over a wide range of scenarios in order to determine the optimal rebroadcast probability for a given node in the network. As we shall discuss below the optimal rebroadcast probability has been found to be p_1=0.7, p_2=0.35, and p_3=0.25 for sparse, medium and dense regions, respectively.

Figure 6.2 explores the SRB results in the three flooding algorithms for a network size of 50 nodes with low mobility conditions of maximum speeds of 2 m/s and 0 pause time. Besides that a medium traffic load is considered, where a constant bit rate of 5 broadcast packets are injected into the network every second the rebroadcast probabilities (p_1, p_2, p_3) in the new highly adjusted probabilistic algorithm have been set as follows: The probability p_1 for nodes located in sparse regions has been varied from 0.1 to 1.0 percent with 0.1 percent increment. The probability p_2 for nodes located in medium regions has been set at $p_2 = p_1/2$. Moreover, the probability p_3 for nodes located in dense regions has been set at $p_3 = p_1/3$. The figure shows that SRB in highly adjusted probabilistic flooding is higher than in the adjusted and fixed probabilistic versions for all of the probability values. While SRB is 62% in highly adjusted probability, it is only 29% in the fixed probability algorithm for p=0.7 and SRB is 46% in the adjusted probability algorithm for the probability p= (0.7, 0.35).

From the conducted simulations it has been found that our new algorithm also manages to achieve good reachability levels of over 95%. This could be achieved when in sparse regions the rebroadcast probability is set at around p_1=0.7 while those located in medium regions have a rebroadcast probability is set at p_2=0.35 also those located in dense regions have a rebroadcast probability is set at p_3=0.25. These probability values will be adopted for highly adjusted probabilistic flooding for the reminder of the present discussion.

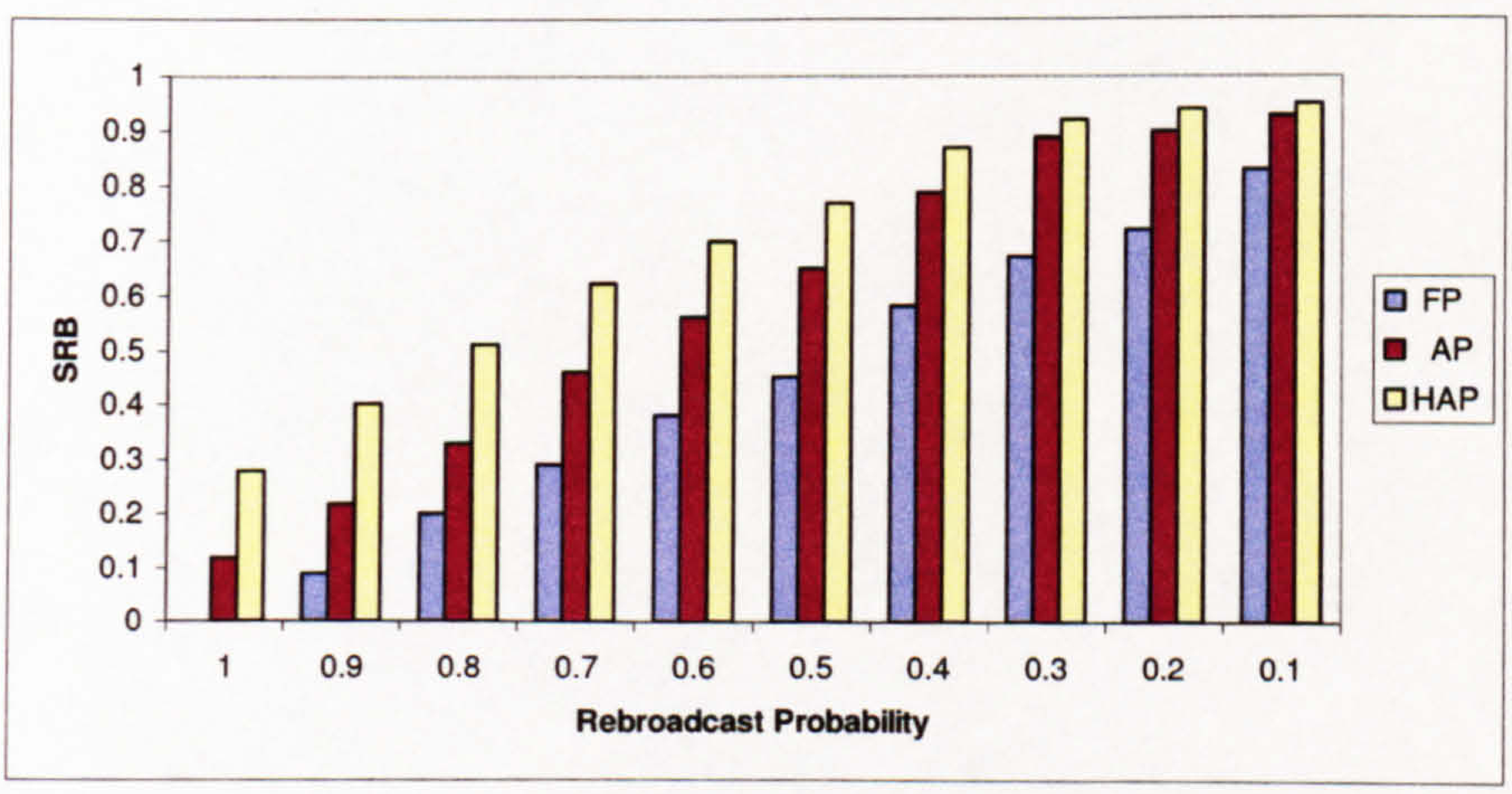

Figure 6.2: SRB vs. rebroadcast probability for a network size of 50 nodes and node speed 2 m/s.

Figure 6.3 explores SRB in the three algorithms for various network mobility conditions where the maximum node speed has been varied from 2 to 20 m/s with no pause time in a network of 50 nodes. The figure reveals that highly adjusted flooding still delivers the best performance over the other algorithms. Nonetheless, it can be noticed that the three algorithms experience a decrease in SRB as mobility increases.

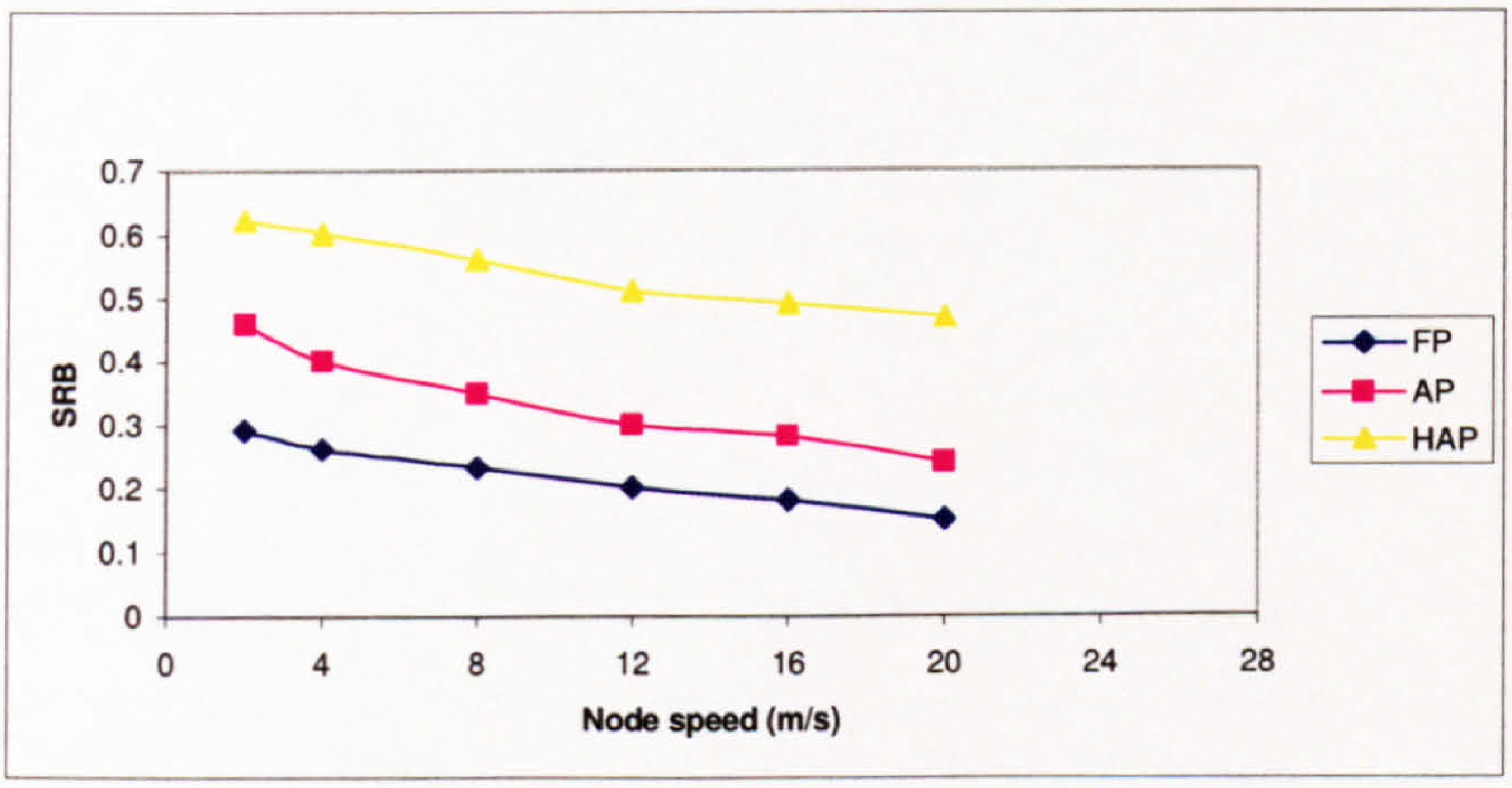

Figure 6.3: SRB vs. node speed 2, 4, 12, 16, 20 m/s for a network size of 50 nodes

In Figure 6.4, we have varied the traffic load by considering three traffic loads, notably 1, 5, and 10 packets/s. The network size has been kept at 50 under low network mobility conditions with a maximum speed of 2 m/s and 0 second pause time. Again, the figure shows that highly adjusted probabilistic flooding can significantly improves SRB at different traffic loads compared to the other two probabilistic schemes.

Figure 6.5 depicts SRB results for different network densities. When the broadcast probability is highly adjusted SRB is higher by 34% in low density networks (e.g., 25 nodes) and 47% in high density networks (e.g., 100 nodes) compared to fixed probability. Furthermore there is a difference between the performance of highly adjusted and adjusted probability in favour of the former in that SRB is higher by 12% and 26% in low and high density networks, respectively.

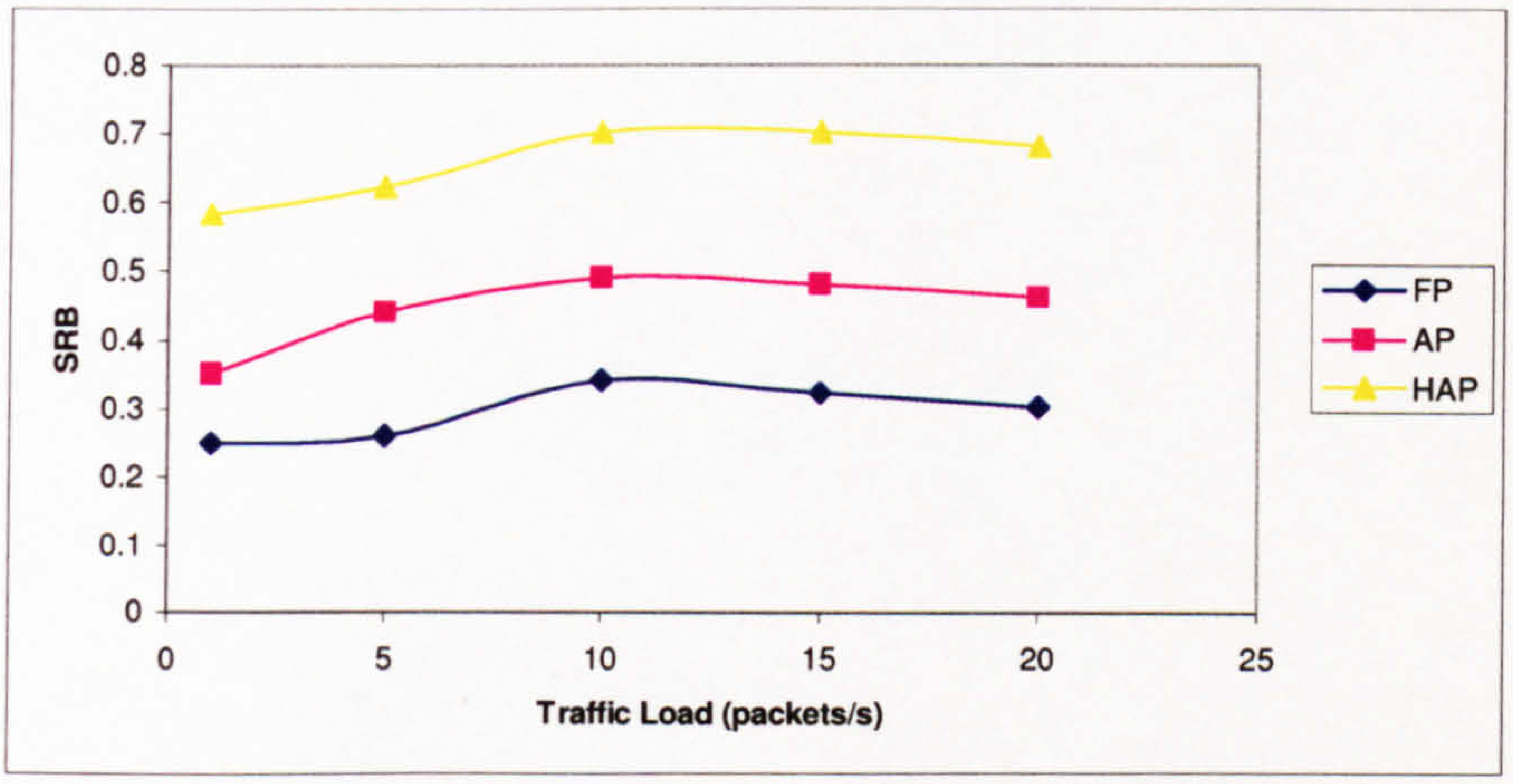

Figure 6.4: SRB vs. traffic load for a network size of 50 nodes and node speed 2 m/s.

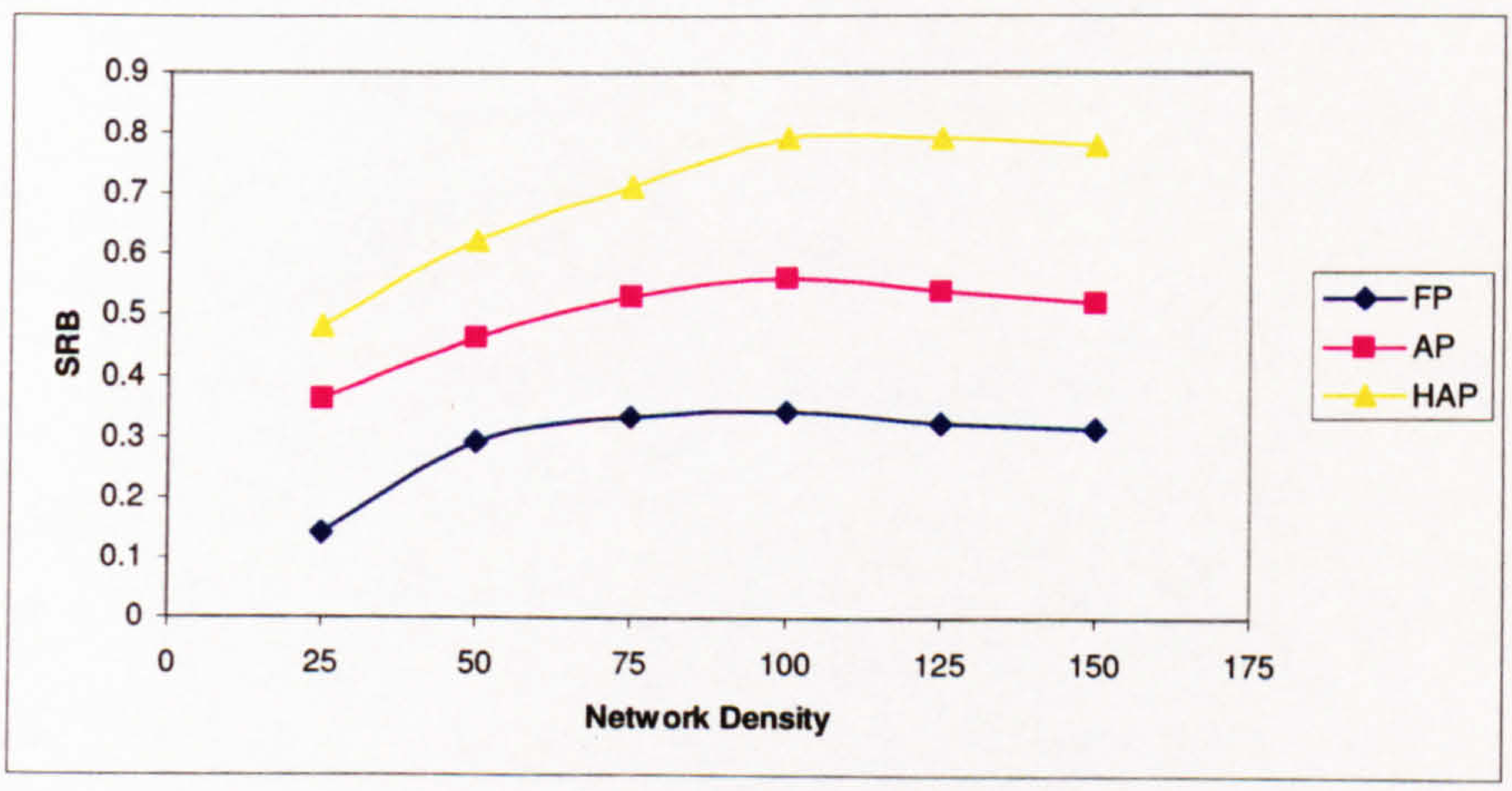

Figure 6.5: SRB vs. network density for node speed 2 m/s.

Reachability (RE):

Figure 6.6 explores RE results in fixed, adjusted, and highly adjusted probability algorithms for a network with 50 nodes at low mobility conditions with a max. speed of 2 m/s and 0 pause time. In the new algorithm the probability p_1 is varied from 0.1 to 1.0 percent with 0.1 percent increment while p_2 and p_3 are set at $p_1/2$ and $p_1/3$, respectively. The figure shows that as the rebroadcasts probability increases RE increases for the three algorithms. Furthermore, the figure reveals that the RE level can be over 95% when the rebroadcast probability is p_1=0.7, p_2=0.35 and p_3=0.25 in highly adjusted probabilistic flooding.

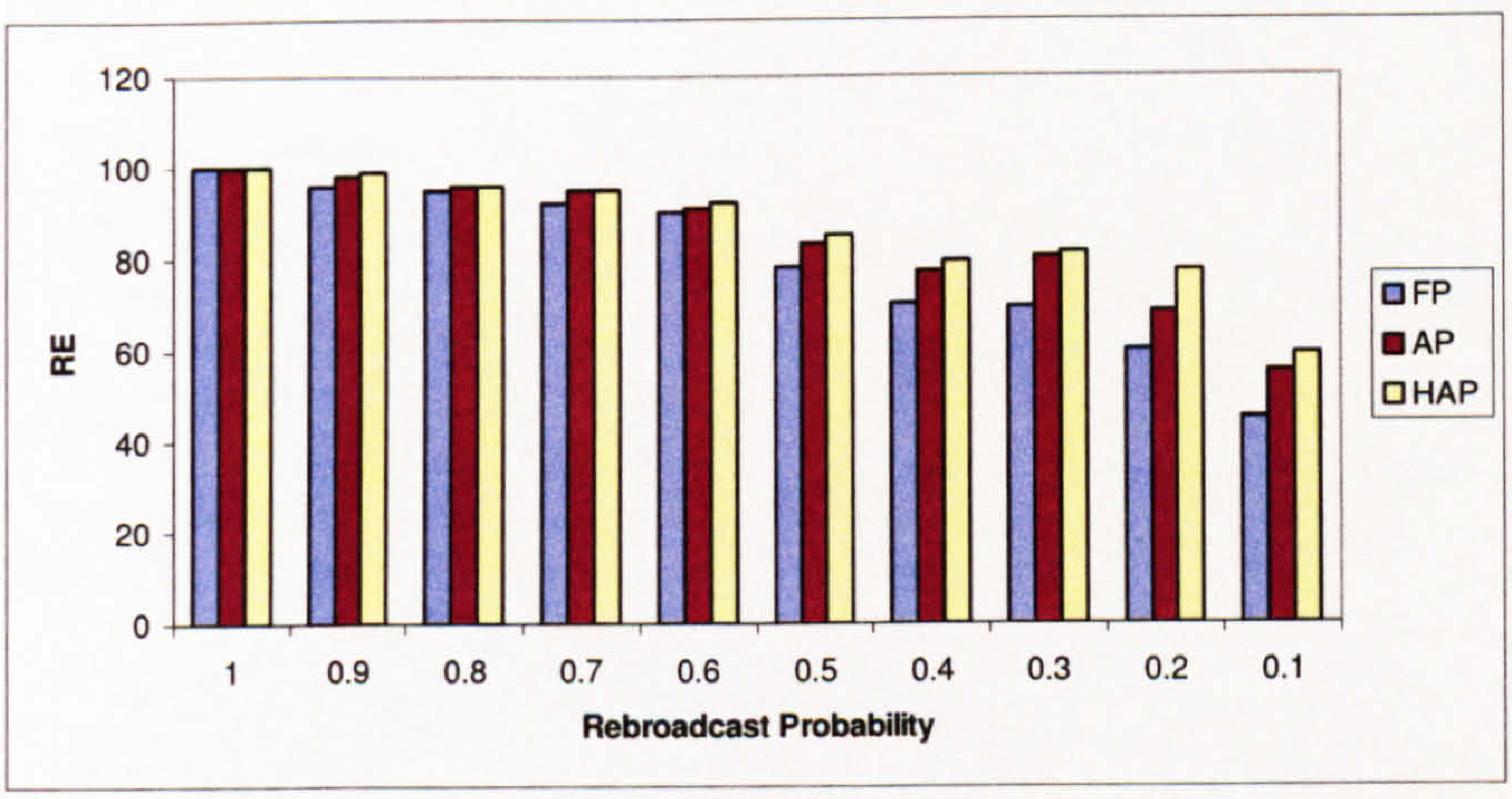

Figure 6.6: RE vs. rebroadcast probability for a network size of 50 nodes and node speed 2 m/s.

Figure 6.7 shows RE results for various network mobility conditions (0 second pause time) with the maximum node speed has been varied from 2, 4, 10 to 20 m/s in a network with 50 nodes. RE increases with faster moving nodes in the three versions of probabilistic flooding,

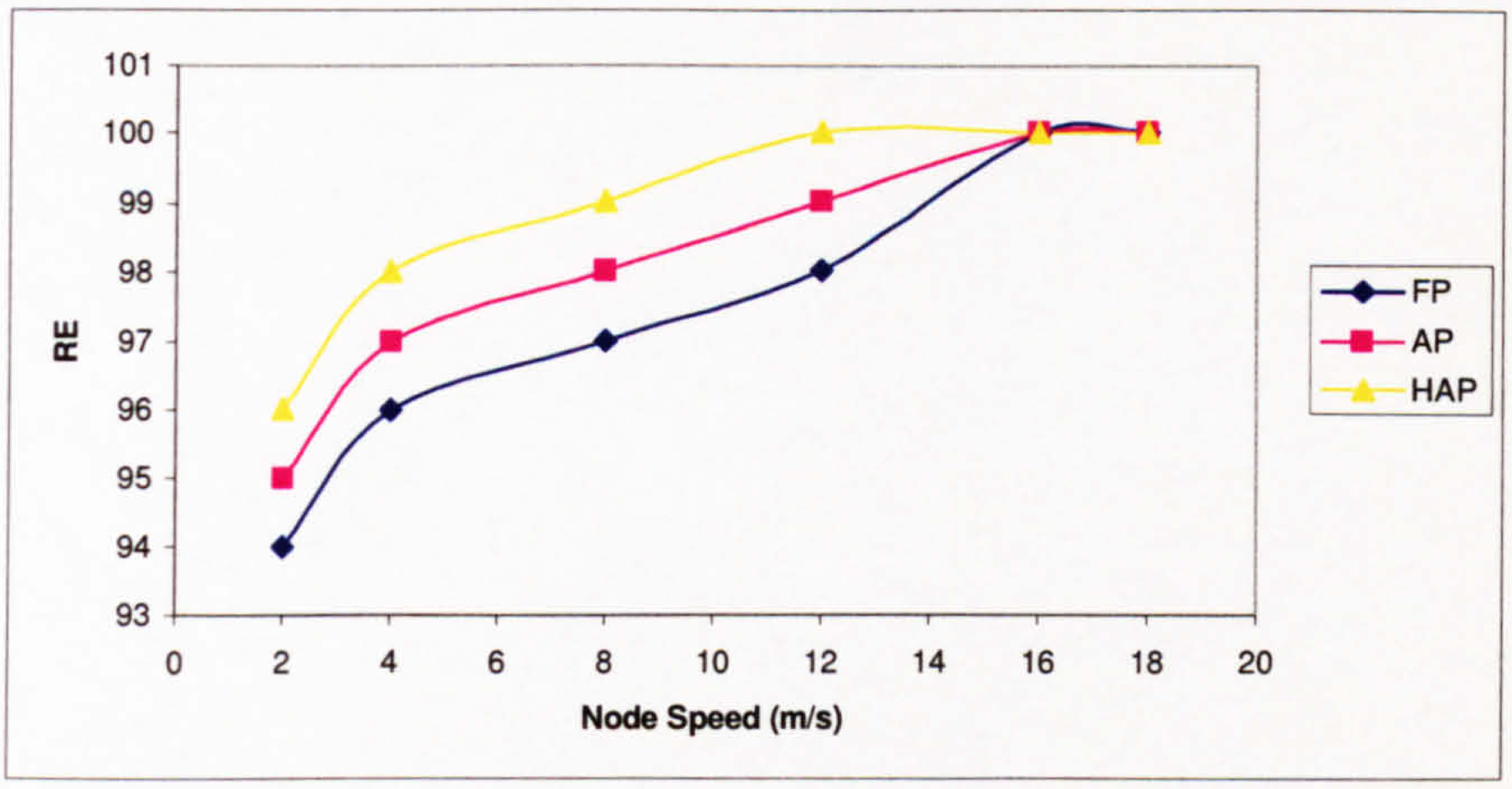

Figure 6.7: RE vs. node speed 2, 4, 12, 16, 20 m/s for a network size of 50 nodes.

In Figure 6.8, the traffic load is varied using different broadcasting rates while the network size is kept at 50 under network mobility conditions (0 second pause time) with the maximum speed of 2 m/s. Again, the figure shows that RE in highly adjusted probability is higher under different traffic loads compared to fixed probability and adjusted probability flooding.

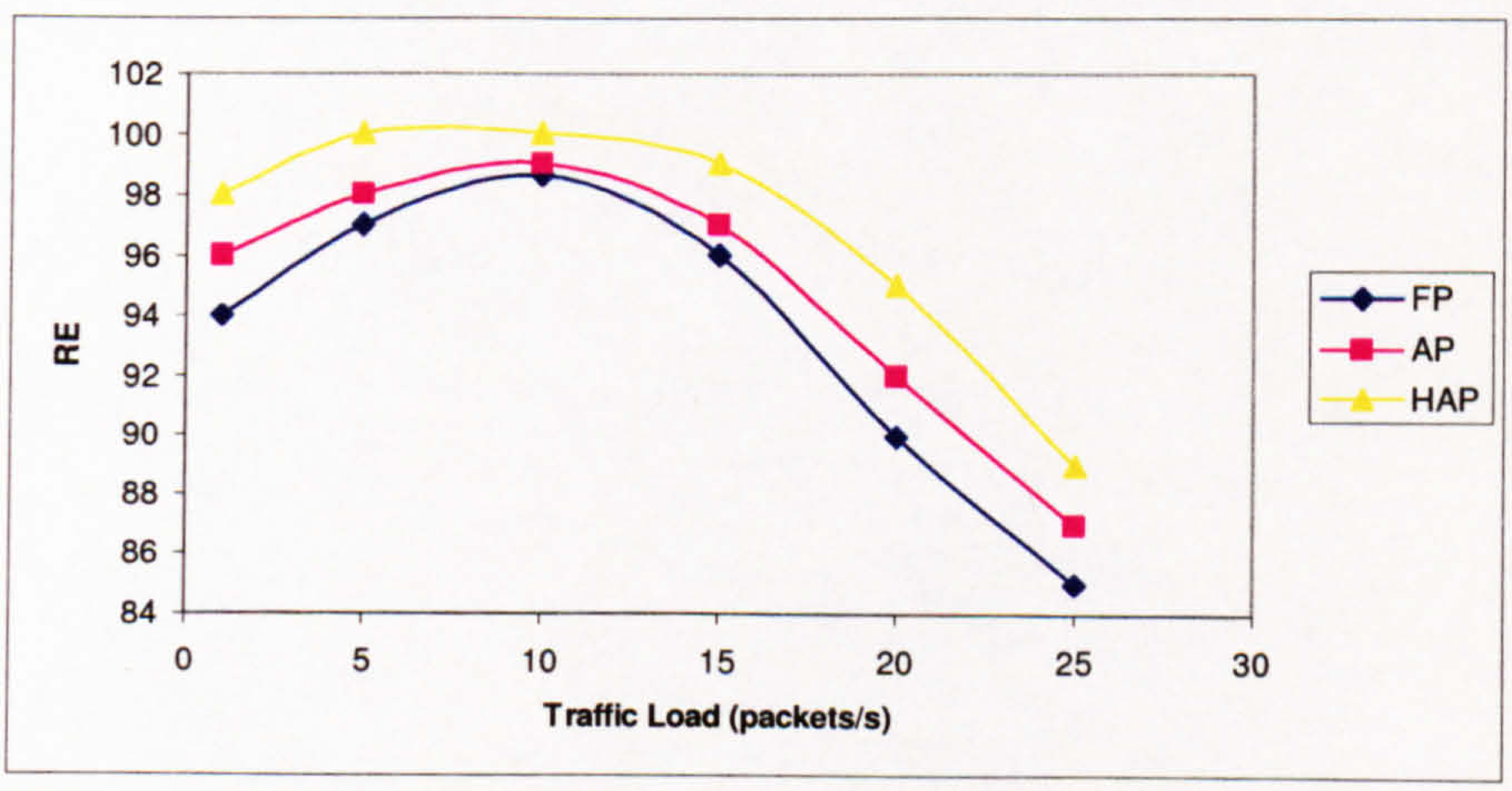

Figure 6.8: RE vs. traffic load for a network size of 50 nodes with node speed 2 m/s.

Figure 6.9 shows that RE increases when network density increases, regardless of what kind of the algorithms is used. The results for highly adjusted flooding shows that RE is above 95% for any network density. In fact, RE in the new algorithm is comparable or higher than in adjusted probability and fixed probability. In higher density networks, i.e., 100 nodes and above, RE in the highly adjusted and fixed probabilistic approaches are comparable; that is RE is close to 100%.

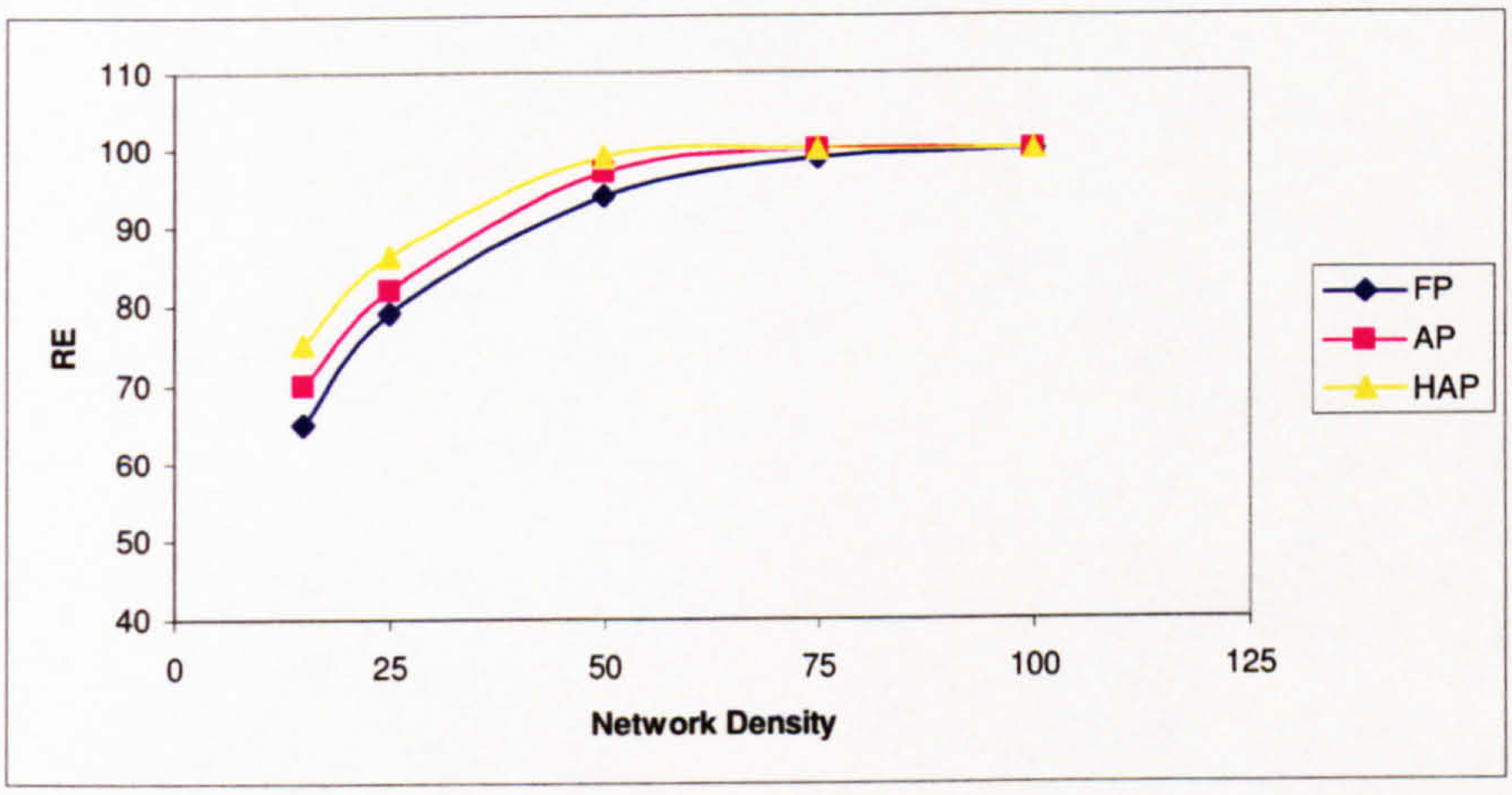

Figure 6.9: RE vs. network density for node speed 2 m/s.

6.4 Conclusions

This chapter has described a new probabilistic algorithm for MANETs referred to as highly adjusted probabilistic flooding, where the rebroadcast probability is set by considering nodes' density regions. In this algorithm, three different forwarding probabilities are assigned to network nodes depending on whether they are located in sparse, medium, or dense regions. Compared against the fixed probabilistic and adjusted probabilistic schemes, simulation results have shown that the new algorithm can improve the saved broadcast up to 47% compared to fixed probability and 26% compared to adjusted, even under conditions of high mobility and high density without degrading reachability. Such improvement is also obtained when various traffic loads are applied to the network.

A natural extension of this research would be to assess whether refining further the forwarding probability using more refined levels for nodes' density regions can lead to further improvement in the performance of probabilistic flooding. Another possible continuation of this research would be to investigate whether our suggested probabilistic schemes could be used to improve the performance of routing protocols in MANETs. Towards this end, our newly proposed algorithms as well as fixed probabilistic flooding have been incorporated in the Ad hoc On-Demand Distance Vector (AODV) routing protocol; one of the well-known and widely studied algorithm over the past a few years. The following chapter and the final part of this thesis will report on the performance results of AODV that adopts probabilistic flooding during the route discovery process and compare them against those of the conventional AODV that employ pure flooding.

Chapter 7

Performance Evaluation of AODV with Probabilistic Route Discovery

7.1 Introduction

Most existing routing protocols that have so far been suggested for MANETs use blind flooding for the propagation of routing control packets, such as Route Request (RREQ) and Route Reply (RREP), during route discovery [23, 24, 29, 36, 41, 43, 44, 49, 56]. This chapter aims to improve the performance of existing routing protocols by reducing the communication overhead due to the use of blind flooding during route discovery. To this end, we have incorporated our new highly adjusted probabilistic flooding algorithm in the existing Ad Hoc on Demand Distance Vector (AODV) routing protocol [36]. AODV is one of the well-known on-demand routing protocols that has been widely studied and analysed over the past few years [36, 46, 48, 50, 52, 54, 60, 61, 63, 65 76]. AODV has a lower routing overhead compared to the traditional proactive routing schemes as it introduces routing overhead only in the presence of data packets that need to be routed.

To the best of our knowledge, this is the first research study that investigates probabilistic flooding in the context of MANETs routing protocols. Our results will reveal that equipping AODV with highly adjusted probabilistic flooding instead of blind flooding greatly helps to reduce the redundant rebroadcast of RREQ packets during the route discovery process. As it will be shown below, AODV with highly adjusted probabilistic flooding manages to achieve superior performance over AODV with blind flooding and even over AODV with fixed probabilistic flooding in terms of a number of important metrics including saved rebroadcasts, reachability, latency, packet delivery ratio and routing overhead.

The remainder of this chapter is organised as follows. Section 7.2 introduces the AODV routing protocol. Section 7.3 conducts a performance evaluation of AODV with highly adjusted probabilistic and compare it against that of AODV with blind flooding and fixed probabilistic flooding. Finally, Section 7.4 provides a summary of this chapter.

7.2 Ad-hoc On-demand Distance Vector (AODV)

AODV is, as the name indicates, a distance-vector protocol [36, 56], that is responsible for routing data between a given pair of nodes in a MANET. It is a reactive routing protocol as it establishes a route to a destination only on demand. AODV as well as many other existing routing protocols use blind flooding to establish routes between a given pair of nodes. AODV uses a similar route discovery and maintenance mechanisms used in DSR

[43, 44, 54] and the sequence number technique used in DSDV [55]. It sets up routes on demand in order to minimise the traffic generated due to broadcasting RREQ packets. Unlike DSDV, AODV does away with the maintenance of the routing table of the entire network.

AODV is considered to be a pure on-demand routing protocol since nodes that are not in the selected path to a destination do not participate in routing decisions or maintain any routes. Routes in AODV are discovered and established and maintained only when and as long as needed. To ensure loop freedom during message routing, sequence numbers are created and updated by each node as used. The sequence numbers also allow the nodes to select the most recent route to a given destination node.

In AODV, a node store some routing information such as destination and next hop addresses as well as the sequence number of a destination. Next to that, a node also keeps a list of the precursor nodes, which route through it, in order to make route maintenance easier after link breakage. To prevent storing information and maintenance of routes that are not used anymore each route has a lifetime. If during this time the route has not been used, it is discarded.

Route Discovery:

Whenever a source needs to communicate with a destination, it checks for an existing route to the destination. If the route is not present, it initiates a route discovery by broadcasting a RREQ packet to its neighbours. The source address and the broadcast *ID* (incremented for every RREQ) generated uniquely identifies a RREQ packet. The RREQ packet is flooded [35, 36, 41, 43, 44, 54, 56] onto the MANET until it reaches the destination or until it reaches a node, which has the latest route to the destination. The route with the highest sequence number indicates the latest route. The destination or intermediate node sends back a RREP packet, which includes the number of hops in-between and a sequence number. RREP is forwarded along the path over which the RREQ was received. Each node receiving the RREP packet creates a forward route to the destination. Thus, each node remembers only the next hop required to reach a given destination, as thus there is no requirement to know the whole route. Each route has associated a timer with it, which indicates the time period for which the route is valid.

If no RREQ packet has been sent within, by default, 1 second each node broadcasts a "Hello" packet to its neighbours in order to keep connectivity up to date. These packets contain the node's IP address and its current sequence number. The "Hello" packets have a TTL value of 1 so that they are not forwarded from the node's neighbours to third parties.

7.3 Performance Evaluation

This chapter assesses the performance of the AODV routing protocol when probabilistic flooding is used for the dissemination of RREQ packets during the route discovery process. The aim is to reduce redundant rebroadcasts during the route discovery phase, and as a result reduce network traffic and thus decrease the probability of channel contention and packet collision. The net effect is that the end-to-end delay and the delivery ratio of data packet are improved.

The traditional AODV protocol employs blind flooding in the route discovery phase. Therefore, all RREQ packets reach their destinations if the network is not partitioned. One other hand, due to the inherent nature of the probabilistic approach, there is a chance that the RREQ packets may not reach the destinations when probabilistic flooding is used during route discovery. In such circumstances, the RREQ request has to be generated if the previous route request failed to reach the destination.

To study the impact of probabilistic flooding on the route discovery process; three versions of AODV have been examined. These are:

- The conventional AODV with blind flooding. Below, this is referred to as AODV-BF for short.
- AODV with fixed probabilistic flooding that has been discussed in Chapter 3. The resulting routing protocol is referred below to as AODV- FP. The rebroadcast probability in AODV- FP is set at p_1 =0.7. Chapter 3 has shown that this probability value enables fixed probabilistic flooding to achieve a high performance level.
- AODV with highly adjusted probabilistic flooding, which has been introduced in Chapter 6. The resulting routing protocol is referred to as AODV-HAP. The rebroadcast probabilities in AODV-HAP are set as follows: p_1=0.7, p_2=0.35 and p_3=0.25. Chapter 6 has shown that these probabilities enable highly adjusted probabilistic flooding to maintain a high performance level.

Simulation Setup:

The network setup discussed in Chapter 6 is used here again, and is briefly described for the sake of completeness. A flat square terrain is used in our simulations with dimensions set to 1000x1000m. The number of network nodes is 50 nodes. Each node can engage in communication transmitting within a 250m radius and having a bandwidth of 2Mbps. The MAC layer protocol is IEEE 802.11[81]. The nodes move according to the random waypoint model [51]. This mobility model is used to simulate 30 topologies in order to achieve a 95% confidence interval in the collected statistics. The speed varies 2 to 20 m/s and pause time 0 second is examined. It is worth noting that in order to compare the three versions of AODV, we have used traffic and mobility models similar to those previously reported for the performance of AODV [36, 56]. The main parameters used in the simulations are summarised in Table 7.1.

Table 7-1: Summary of the parameters used in the simulation experiments.

Parameter	Value
Transmitter range	250 meters
Bandwidth	2Mbps
IFQ type Queue/DropTail/PriQueue	50 packets
Simulation time	900 seconds
Pause time	0 seconds (continuous mobility)
Topology size	1000×1000 meter^2
Number of node	50
Data traffic, packet size	CBR, packets of 512 bytes
Maximum speed	2,4,8,12, 20 m/s
Hello packet	12 bytes

The simulation time is 900 sec, and identical mobility and traffic scenarios are used for the three routing protocols. Nodes are placed uniformly over the terrain. A source generates a CBR traffic flow consisting of 512-bytes data packets. The source-destination pairs are chosen randomly among the nodes in the network. Flows last, on average, for 30s with a duration which follows an exponential distribution. Source nodes keep active flows during the simulation time (new destinations are randomly selected as required). During the simulation time and at any given time there are always a number of active flows. Nodes start transmission at 50s plus an offset uniformly chosen over a 5s period to avoid synchronization in their initial transmissions.

The metrics used in the performance analysis include saved rebroadcasts, reachability, average end-to-end delay, routing overhead and packet delivery ratio.

Saved Rebroadcasts (SRB):

Figure 7.1 depicts SRB in AODV-F, AODV-FP, and AODV-HAP as a function of the traffic load that is varied by using different number of CBR source-destination connections. The network size is kept at 50 nodes which move with a max. speed of 2 m/s. The number of RREQ packets increases as the traffic load increases. This results in an increase in the broadcast activity of RREQ packets inside the network. The figure reveals that AODV-HAP significantly improves SRB compared to other routing protocols. Furthermore, AODV-HAP has the highest SRB for all traffic loads and the performance advantage of AODV-HAP increases as the traffic load increase. The difference in performance in favour of AODV-HAP ranges from 60% to 70% compared to AODV-BF and from 20% to 30% compared to AODV-FP.

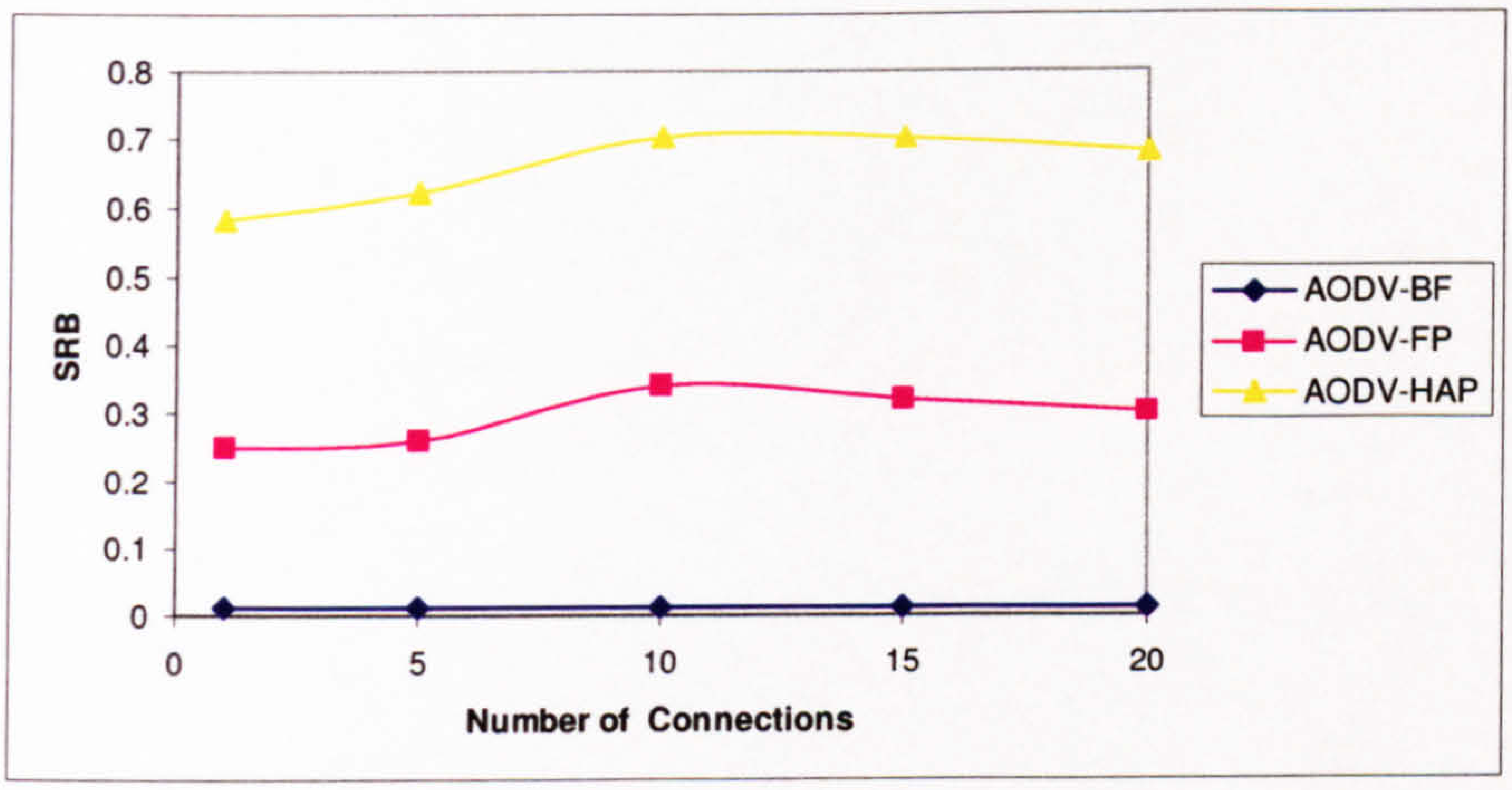

Figure 7.1: SRB vs. traffic load for a network size of 50 nodes and node speed of 2 m/s.

Figure 7.2 depicts the performance of the three versions of AODV with different mobility settings when 10 connections of source destination pairs are used. The SRB results reveal that AODV-HAP outperforms AODV-FP and AODV-BF at all node speeds, when it is varied from 2 to 20 m/s. For instance, AODV-HAP outperforms AODV-FP in terms of SRB by 30% and AODV-BP by 62% when the node speed is 2 m/s. When the node speed increases SRB slightly decreases. For instance, SRB decreases from 62% to 47% in AODV-HAP and from 29% to 15% in AODV-FP when the node speed is increased from 2 m/s to 20 m/s.

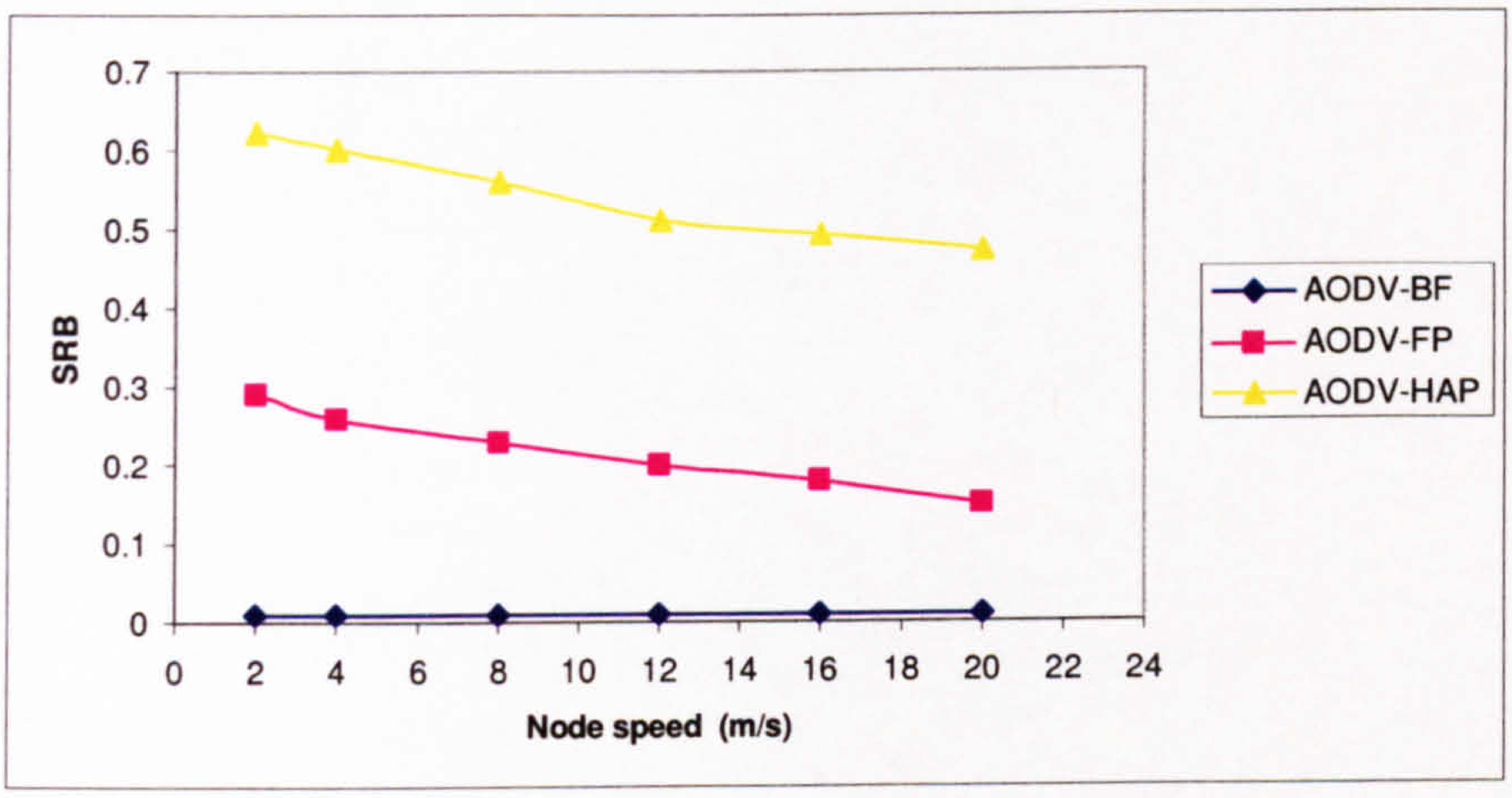

Figure 7.2: SRB vs. node speed 2, 4, 10, 16, 20 m/s for a network size of 50 nodes.

Reachability (RE):

This metric provides an indication of the number of successful paths established by the routing protocol for the delivery of data packets. Figure 7.3 shows RE results for different traffic loads varying from 1 to 20 connections of source- destination pairs. The network size is kept at 50 under network mobility conditions (0 second pause time) with the max. speed of 2 m/s in the AODV-BF, AODV-FP and AODV-HAP. Again, AODV-HAP significantly improves RE at different traffic loads compared AODV-FP and AODV-HAP. However, the RE starts to decrease when traffic load increases; i.e., when over 10 connections of source destination pairs are used. For instance, RE decreases from 100 % to 89 % in AODV-HAP when the traffic load increases from 10 to 20 connections of source destination pairs. Similarly RE decreases from 100 % to 85% in both DV-FP and AODV-BF. Furthermore, RE in AODV-HAP is higher by 6 % and 9 % compared to AODV-FP and AODV-BF, respectively, when the traffic load is relatively high; 20 connections of source destination pairs are used.

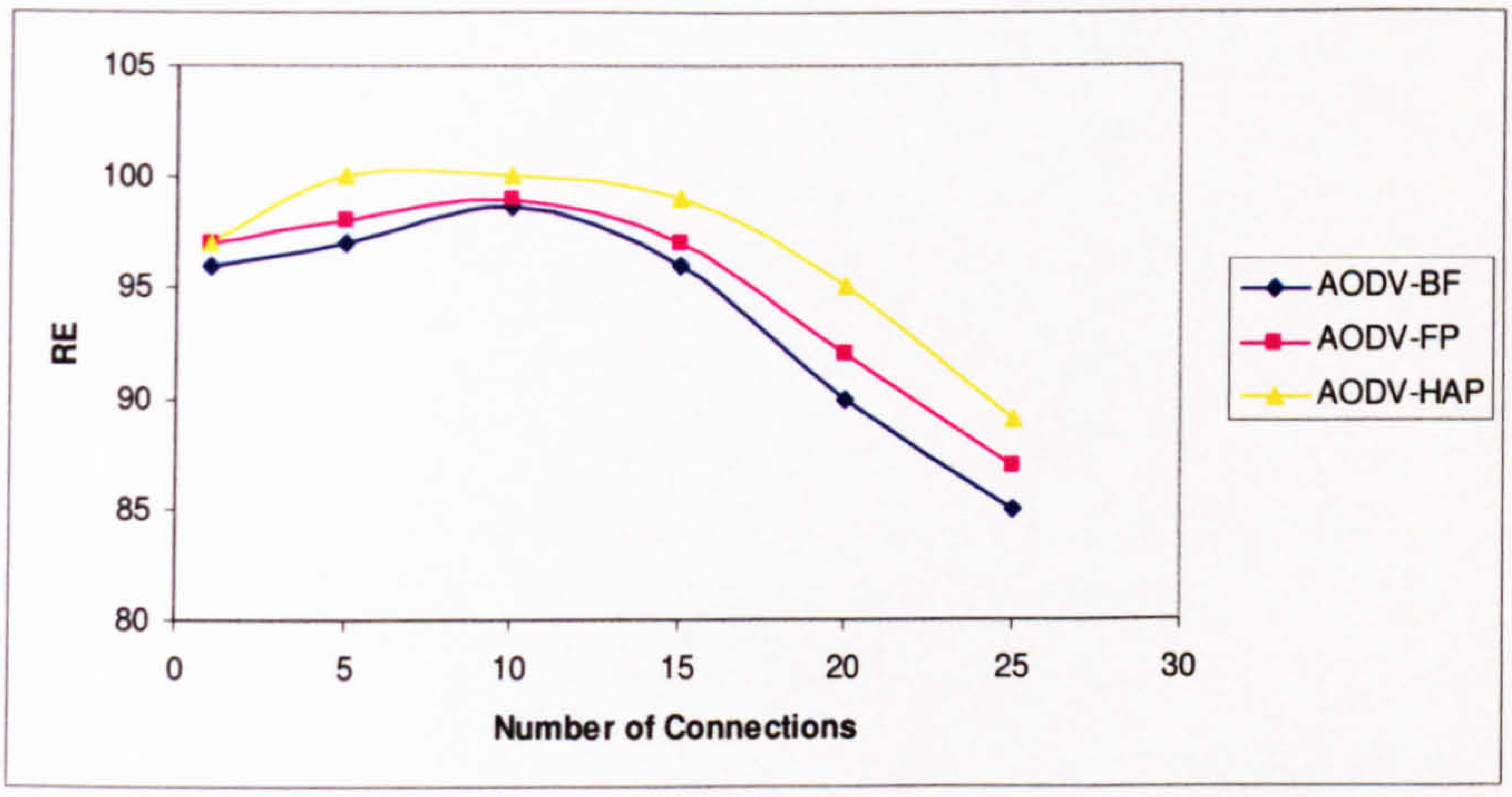

Figure 7.3: RE vs. traffic load for a network size of 50 nodes and with node speed 2 m/s.

Figure 7.4 shows RE for a varying degree of mobility when 10 connections of source destination pairs are used. The figure shows that RE increases when mobility increases, regardless of the routing protocol. AODV-HAP has the best performance in terms of reachability which is close 100%. On the other hand, the results for AODV-BF and AODV-FP show that RE is above 95% when node speed 2 m/s. For higher node mobility, e.g., at the node speed 12 m/s and above, RE is close to 100% in the three routing protocols.

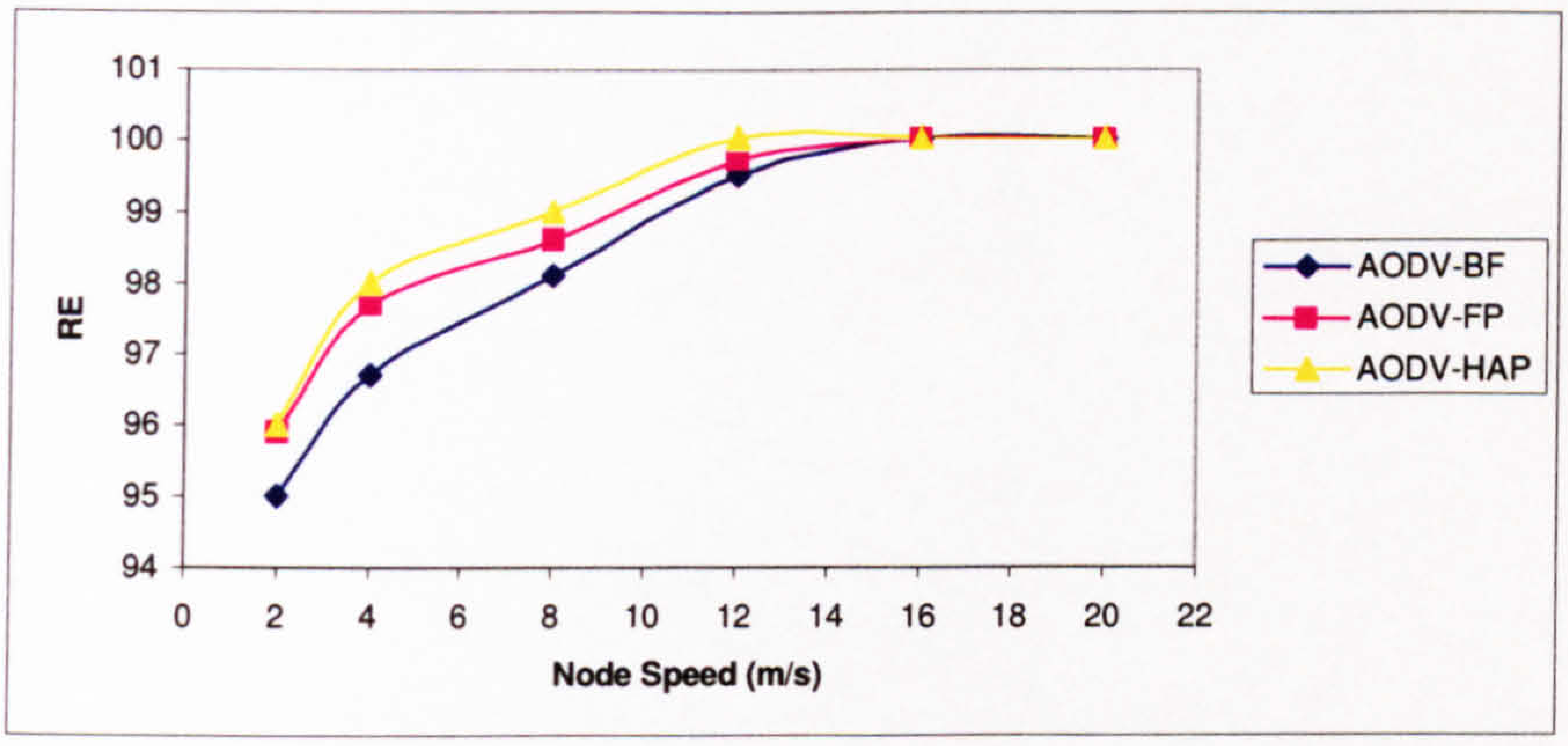

Figure 7.4: RE vs. node speed 2, 4, 8, 12, 16, 20 m/s for a network size of 50 nodes

Average end-to-end delay (Latency):

The average end-to-end delay (or latency) is the time between when a source node sends a data packet until the packet reaches the destination node. Figure 7.5 shows the end-to-end delays of data packets in the three routing protocols for different traffic loads. The number of total packets transmitted on the wireless channel has a significant impact on latency. If the number of packets is high, then the number of collisions is high, and in turn lead to more retransmissions. As a result, packets experience high latencies. As expected, data packets in AODV-HAP experience a lower latency than in AODV-FP and AODV-BF. This is due to the fact that there are higher number of redundant rebroadcasts of RREQ packets in AODV-BF and AODV-FP. This causes contention and collision, and as a result many RREQ packets fail to reach the destinations. As a consequence, another RREQ packet is initiated and the overall latency to establish route increases.

For instance, latency increases from 0.05 to 0.92 sec in AODV-HAP when the traffic load increases from 1 to 20 connections of source destination pairs. Similarly, latency in

AODV-FP increases from 0.05 to 1 sec whereas it increases from 0.06 to 1.17 sec in AODV-BF. Furthermore, latency in AODV-HAP is lower by 0.007 and 0.012 sec than in AODV-FP and AODV-BF, respectively, when traffic load is light; i.e., 1 connection of source destination pair is used. On the other hand, latency in AODV-HAP is lower by 0.080 and 0.252 sec than in AODV-FP and AODV-BF, respectively, when traffic load is relatively higher; i.e. 20 connections of source destination pairs are used.

Figure 7.6 compares the end-to-end latency for different mobility sittings when the number of connections in the network is fixed at 10. The figure shows again that in AODV-HAP data packets experience a lower latency than in AODV-BP and AODV-FP.

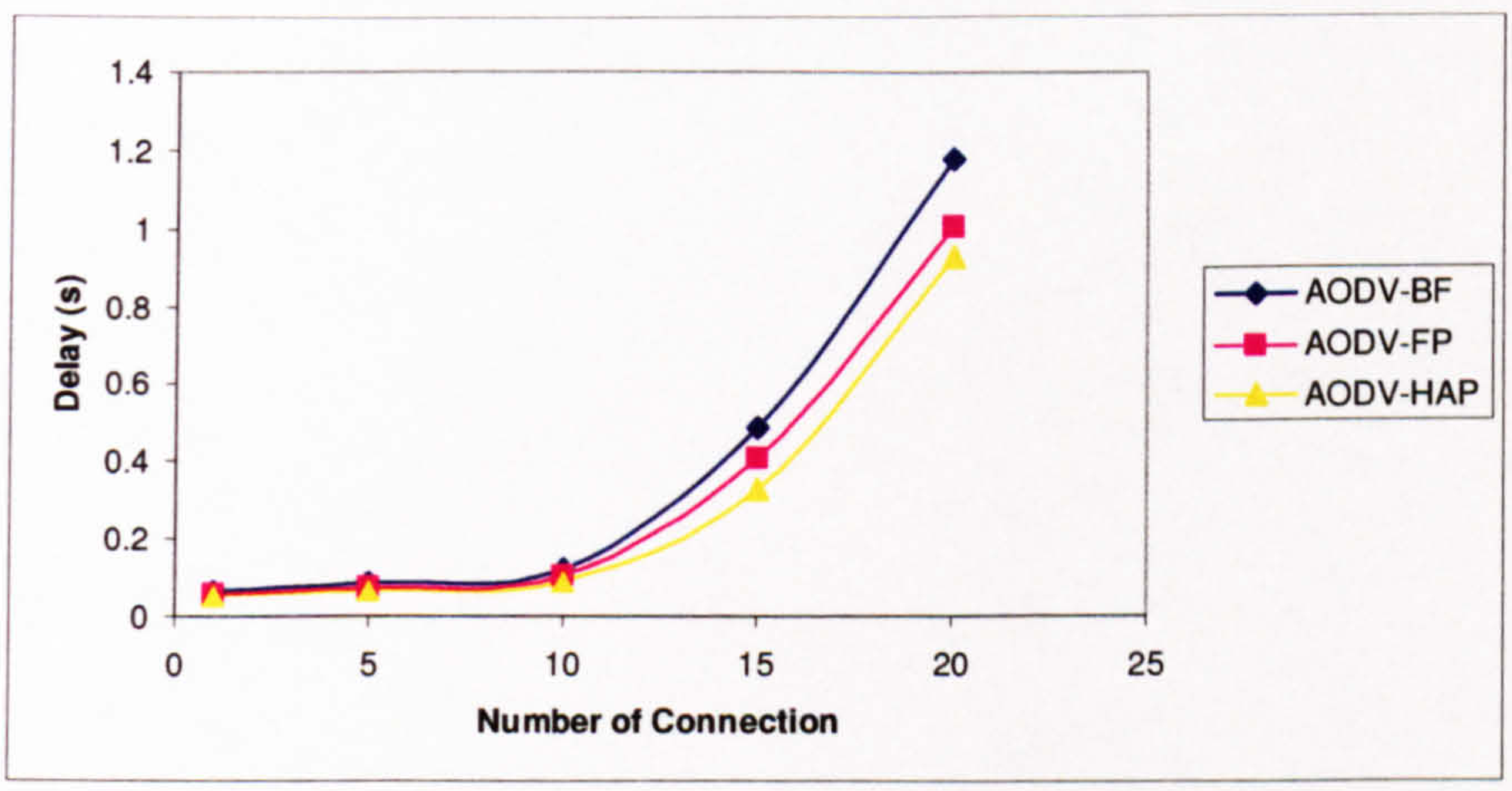

Figure 7.5: Delay vs. traffic load for a network size of 50 nodes and with node speed 2 m/s.

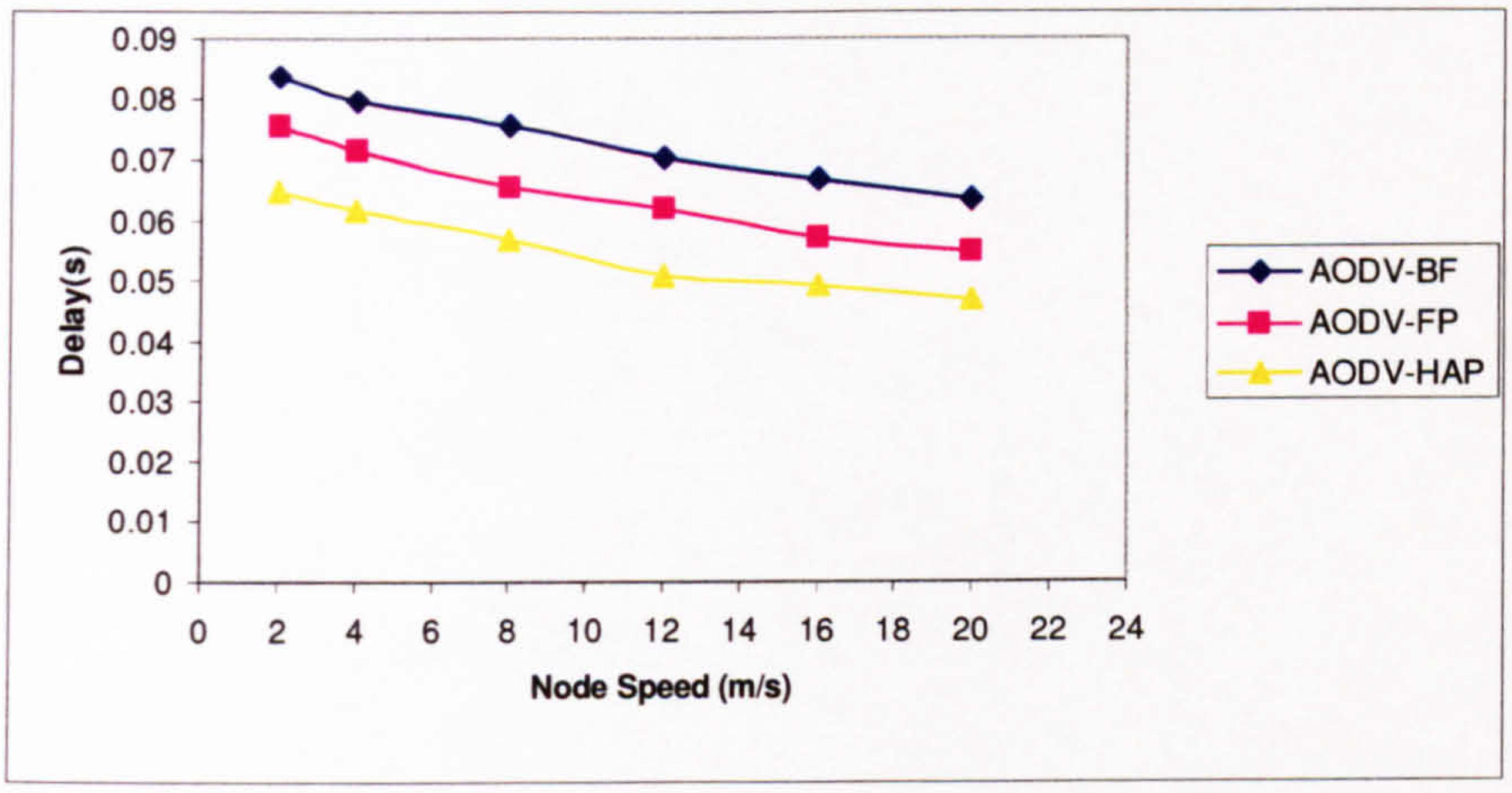

Figure 7.6: Delay vs. node speed 2, 4, 8, 12, 16, 20 m/s for a network size of 50 nodes.

The Packet Delivery Ratio:

The packet delivery ratio is an important metric that measures the ratio of data packets successfully delivered to their destinations to those generated by the constant bit rate (CBR) sources. We compare the packet delivery ratio of the three version of AODV against the traffic load by varying the number of connections in the network. Figure 7.7 reveals that the packet delivery ratio decreases when traffic load increases. The more connections there are, the more RREQ packets are generated, leading to more rebroadcasts and higher bandwidth consumption and thus resulting in a lower packet delivery ratio. The figure also shows that AODV-HAP outperforms both AODV-BF and AODV-FP when traffic load gets heavier; e.g. when number of connection is greater than 10 connections. However, the packet delivery ratio starts to decrease when the traffic load increases; when over 10 connections of source destination pairs are used. For instance, the packet delivery ratio in AODV-HAP decreases from 95% to 79% when the traffic load increases from 10 to 20 connections of source destination pairs. It decreases from 90% to 64% in AODV-FP and from 83% to 61% in AODV-BF. Furthermore, the packet delivery ratio in AODV-HAP is higher by 12% and 19% than in AODV-FP and AODV-BP, respectively, when the traffic load is heavy; e.g., 20 connections of source destination pairs are used.

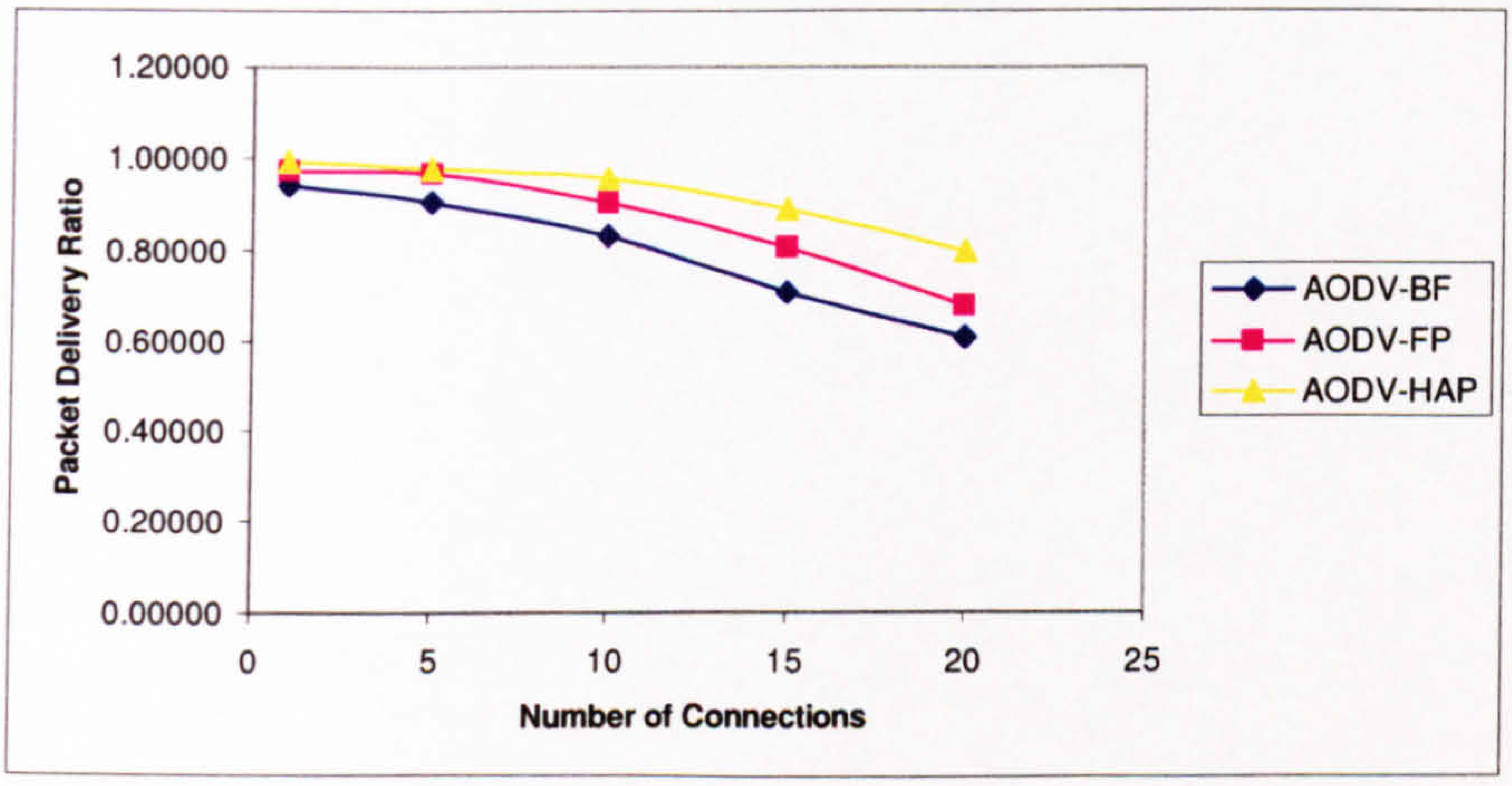

Figure 7.7: Packet delivery ratio vs. traffic load for a network size of 50 nodes and speed 2 m/s.

Figure 7.8 shows the packet delivery ratio in AODV-BF, AODV-FP and AODV-HAP for different mobility scenarios when the number of connections in the network is fixed at 10. When node mobility increases the packet delivery ratio decreases. That is because the faster the nodes move, the more frequently link breakages occur i.e. more RREQ packets fail to reach their destinations. In such circumstances, more RREQ packets are generated and retransmitted, which lead to a higher chance of collision due to the increase in the amount of controls packets generated into the network.

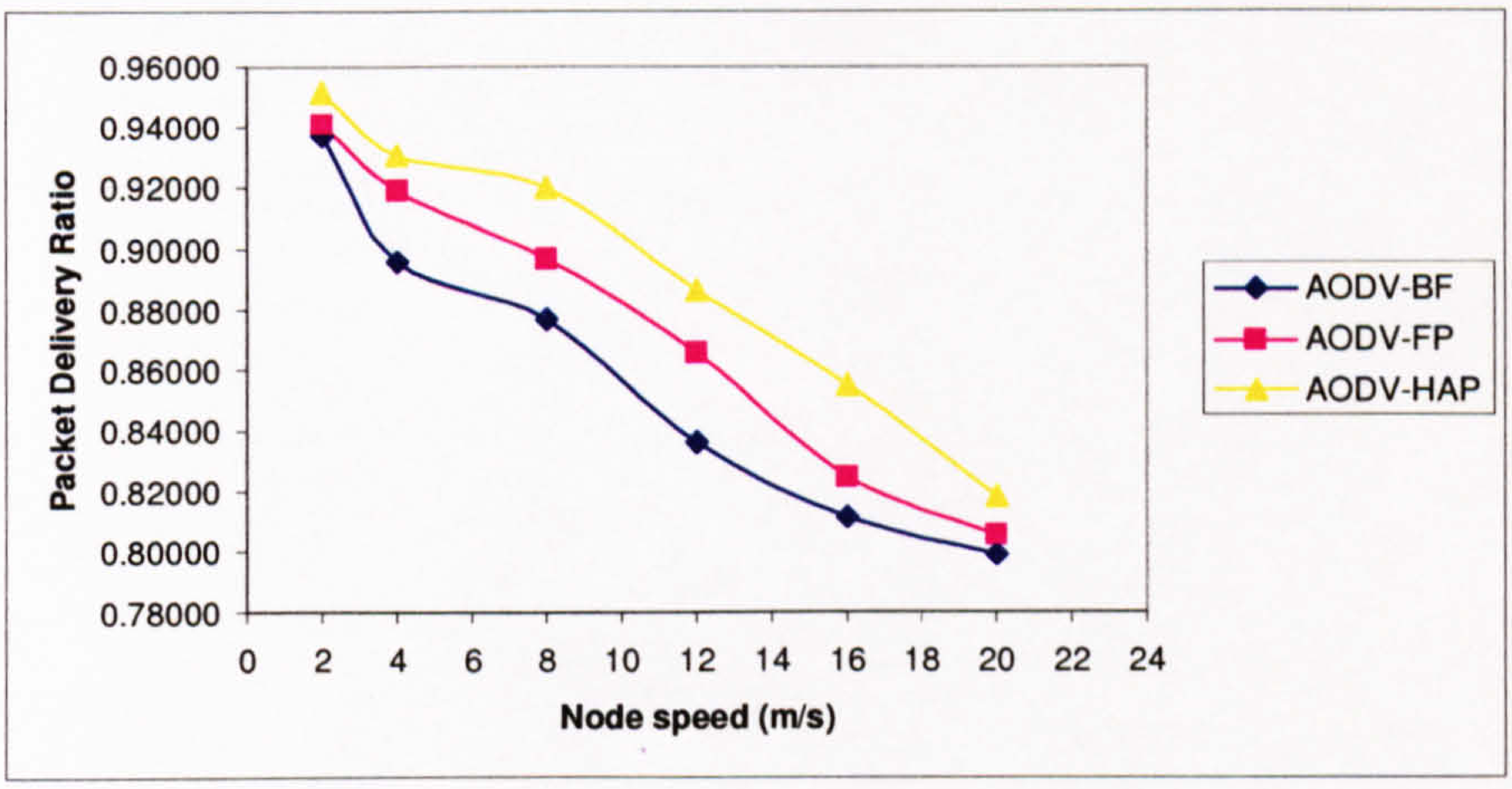

Figure 7.8: Packet delivery ratio vs. node speed 2, 4, 8, 12, 16, 20 m/s for a network size of 50 nodes.

Routing Overhead:

The routing overhead estimates the number of RREQ packets transmitted for the purpose of routing data packets during the whole simulation period. For RREQ packets that are sent over multiple hops, each transmission over one hop is counted as one transmission in AODV-BF, AODV-FP and AODV-HAP. Figure 7.9 shows the routing overhead normalized over the number data packets successfully delivered to their destinations against the traffic load in a network containing 50 nodes which move with a speed of 2 m/s. As revealed by the figure, AODV-HAP incurs a lower routing overhead compared to AODV-BF, AODV-FP.

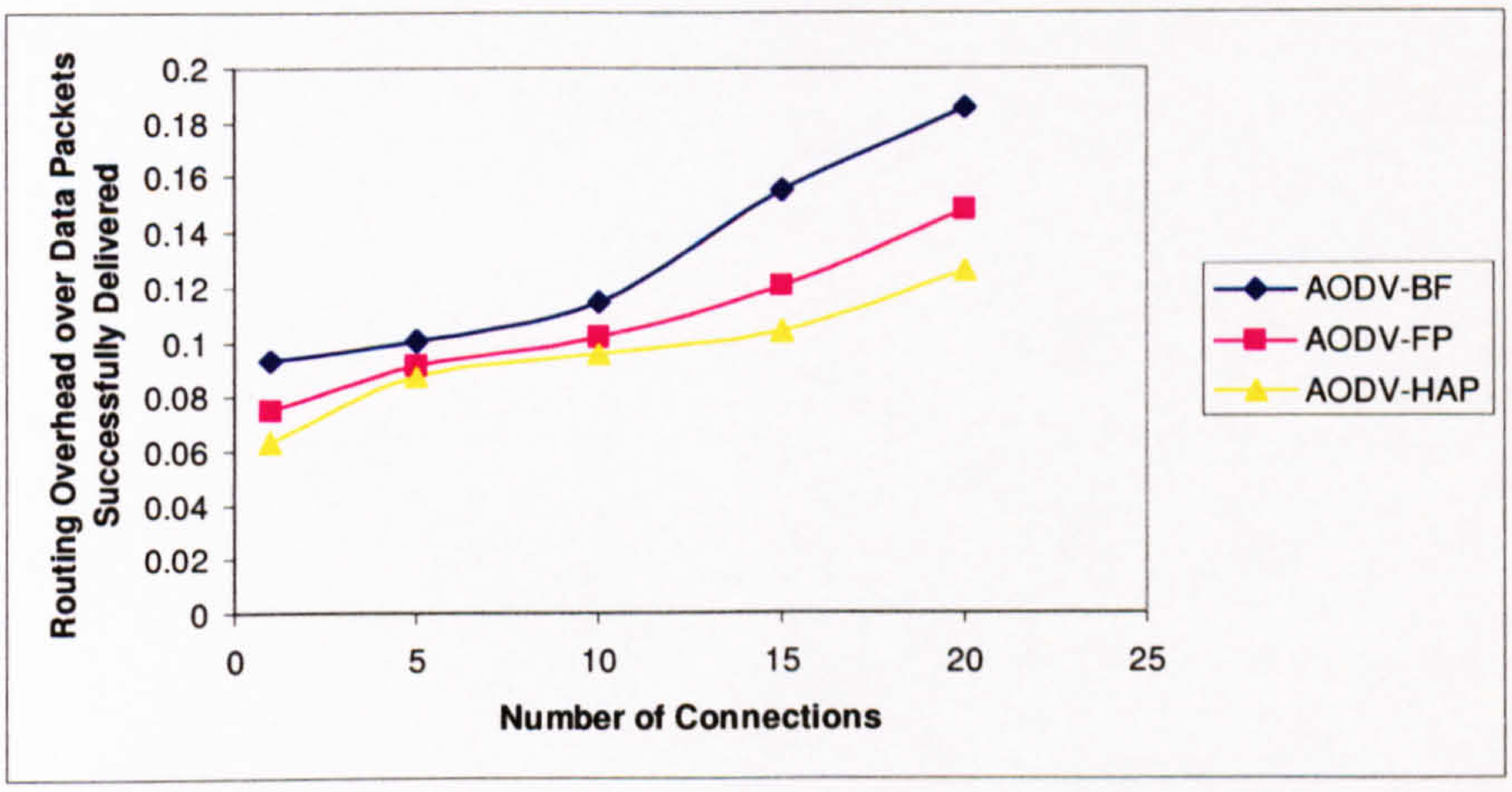

Figure 7.9: Routing overhead vs. traffic for a network size of 50 nodes and with node speed 2 m/s.

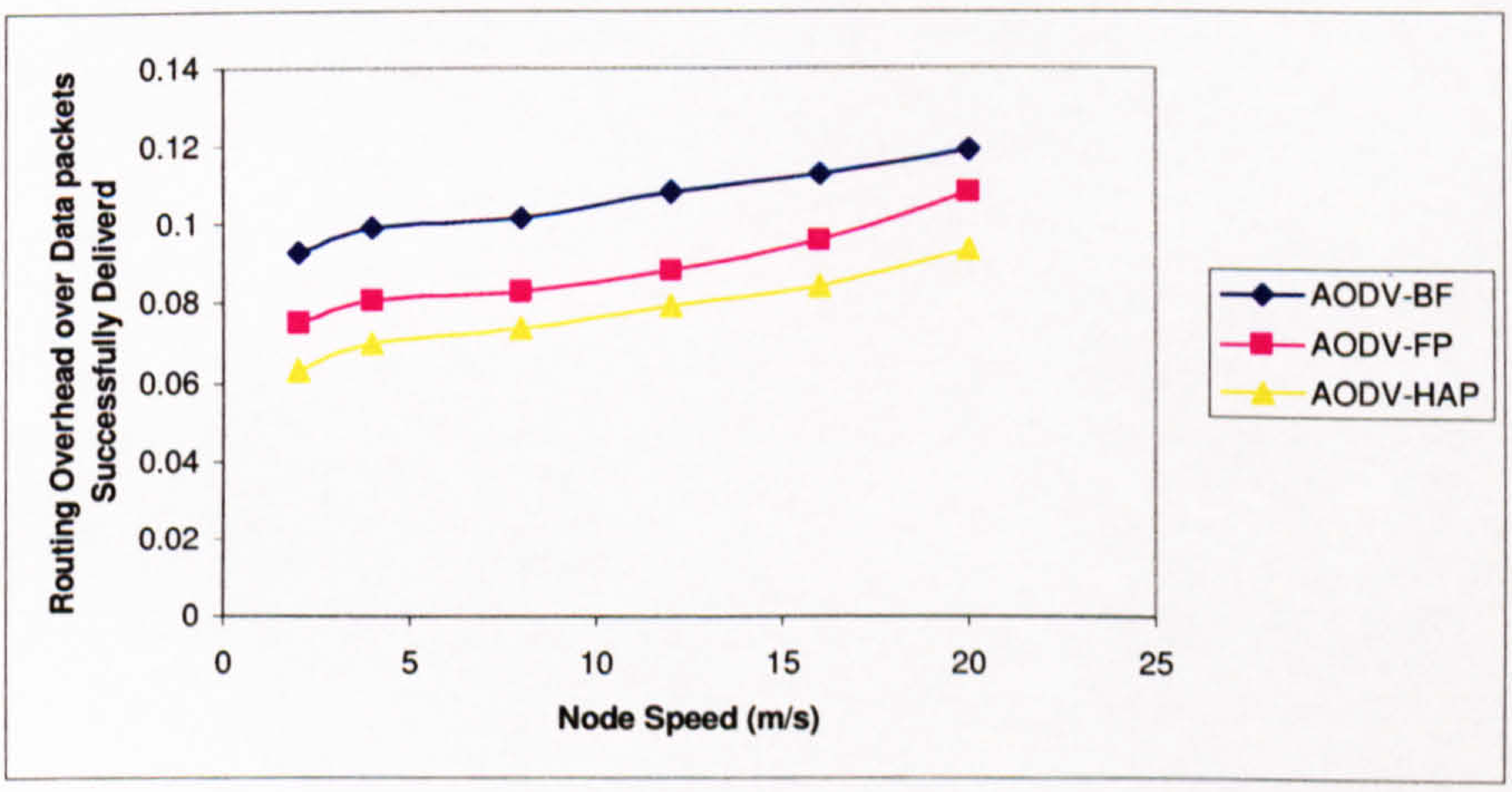

Figure 7.10: Routing overhead vs. node speed 2, 4, 8, 12, 16, 20 m/s for a network size of 50 nodes.

Figure 7.10 shows the routing overhead of AODV-BF, AODV-FP and AODV-HAP with different mobility scenarios when the number of CBR connections is set at 10. When node mobility increases, more RREQ packets fail to reach their destinations. In such conditions more RREQ packets are generated and retransmitted, which lead to higher chance of collision due to the increase in the controls packets. For instance, the normalized the routing overhead over the number data packets successfully delivered to their destinations in AODV-HAP increases from 0.062 to 0.093 when the node speed increases from 2 m/s to 20 m/s. On the other hand, it increases from 0.074 to 0.1 in AODV-FP, and from 0.092 to 0.11 in AODV-BF.

The performance results reported in my algorithms have been restricted to one hop neighbourhood information. A possible continuation of this research would be to run experiments in order to evaluate the performance merits of using two or three hop neighborhoods information for setting the re-broadcasting probability. Also, we have used the broadcast packets of size 512 bytes. If the broadcast packets are very short, the overhead involved in the exchange of Hello packets might outweigh the performance benefits of our algorithms. This is because the analysis done in CHP5 about the HELLO (using rates) assumed that the packet is relatively long 512 bytes.

7.4 Conclusions

In this chapter, the new highly adjusted probabilistic flooding algorithm has been incorporated in the AODV routing protocol for disseminating Route Requests (RREQ) packets in order to improve the route discovery process. The new variant of AODV has been referred to as AODV-HAP for short. For the purpose of the present study, two other variations of AODV have also been discussed. First, AODV with fixed probabilistic flooding, and has been referred to as AODV-FP. Second, the traditional AODV with blind flooding, and has been referred to as AODV-BF. Our comparative analysis has revealed that for most considered cases AODV-HAP has superior performance characteristics over those of AODV-FP and AODV-BF.

Extensive simulation experiments have shown that AODV-HAP has the highest SRB over under a variety of traffic conditions. The difference in SRB performance in favour of AODV-HAP can range from 60% to 70% compared to AODV-BF and from 20% to 30% AODV-FP. Moreover, AODV-HAP manages to achieve a high reachability level while maintains a lower end-to-end delay for data packets compared to AODV-BF and AODV-FP. For instance, the end-to-end delay in AODV-HAP is lower by 08% and 25% sec than in AODV-FP and AODV-BP, respectively, when the traffic load is high; e.g., 20 connections of source destination pairs are used.

When node mobility increases, route breakage become occur more frequently, and as a consequence RREQ packets fail to reach their destinations. More RREQ packets are generated and retransmitted, which lead to a high chance of collision due to the increase in the number of controls packets inside the network. Nonetheless, the results have revealed that AODV-HAP manage to achieve a higher delivery ratio of data packets compared to AODV-BF and AODV-FP while keeping a lower routing overhead for different mobility scenarios. For instance, the delivery ratio in AODV-HAP is higher by up to 12% and 19% than in AODV-FP and AODV-BF when the node speed is 2 m/s, and by 7% and 10% when the node speed is 12 m/s. This is achieved with a routing overhead in AODV-HAP that is lower by up to 19% and 28% than in AODV-FP and AODV-BF, respectively.

Chapter 8

Conclusions and Future Directions

8.1 Summary of the results

The major focus of the present thesis has been on the design of new dynamic probabilistic flooding (or broadcasting) algorithms for Mobile Ad hoc Networks (MANETs) that can overcome the limitations of previous flooding schemes and deliver improved support for MANET applications. Summarised below are the major contributions of this research work.

The first part of this thesis has classified existing broadcast algorithms into two main categories: *deterministic* and *probabilistic* approaches. In the first category, algorithms are further divided into *proactive* and *reactive* schemes. In proactive schemes [4, 6, 11, 19, 21, 22, 82, 90], a node selects some of its 1-hop neighbours as re-broadcasting nodes. When a node receives a broadcast packet, it drops the packet if it is not designated as a rebroadcasting node; otherwise, it recursively chooses some of its 1-hop neighbours as rebroadcasting nodes and then forwards the packet to them. In reactive schemes [1, 16, 24, 27, 31, 75, 77, 82, 88, 89, 94], each node determines by itself whether or not to forward a broadcast packet. In general, however, these techniques are not adaptive enough to cope with high node mobility. This is due to the fact that when the network topology changes frequently, the overhead of discovering and maintaining local network topology (within two or more hops) for each node increases, and may outweigh any benefit from the reduction in retransmissions [1,16, 27, 82, 88, 89]. Furthermore, for proactive techniques, the task of selecting a suitable set of nodes to forward the broadcast packets is not trivial and requires significant computation on the mobile nodes; it was shown in [19, 21, 22, 82, 90] that finding the optimal set of rebroadcasting nodes is an NP-hard problem.

Broadcasting algorithms in the second category use probabilities to help a node decide whether it rebroadcasts its packet or not. One of the main advantages of this category of algorithms is that they are simpler and easier to implement then their deterministic counterparts. Although probabilistic flooding schemes have been around for a relatively long time, there has not been so far any attempt to analyse their performance behaviour in a MANET environment. The second part of this thesis has analysed the effect of some of the most important parameters in a MANET system, such as node mobility, network density, and traffic load, on the performance of the probabilistic approach to flooding in MANETs. In this approach, all the nodes use the same fixed probability for re-broadcasting packets in the network. Extensive ns-2 simulations have revealed that node mobility has a substantial effect on the saved rebroadcast (SRB) and reachability metrics. The results have shown that for different rebroadcast probabilities, as the node speed increases, SRB and reachability values increase. For example, SRB increases by 20% when the node speed increases from 2m/s to 20 m/s. Moreover, reachability increases by

10% when the node speed increases from 2m/s to 20m/s. Similar performance trends have been observed when the other system parameters, such as network density and traffic load, have been examined in that they have been found to have an impact on the degree of reachability and the number of saved rebroadcasts achieved by the probabilistic broadcasting scheme.

The third part of this thesis has analysed extensively the topological characteristics of a MANET when nodes move according to the widely-adopted random way point mobility model [51]. As expected the denser is the network region is, the higher is the number of neighbours of given node. Similarly, the sparser the network region the lower the number of neighbours a node in that region will have. A number of simulation experiments have been performed in order to determine the minimum, average, and maximum number of neighbours for a given node in the network for a wide range of scenarios.

The fourth part of this thesis has proposed two new probabilistic algorithms, referred to as *adjusted probabilistic* and *highly adjusted probabilistic flooding*, respectively, that dynamically alter the rebroadcasting probability using one-hop neighbourhood information. This is done based on locally available neighbourhood information (e.g., the minimum, average, and maximum number of neighbours) and without requiring any assistance from distance measurements or exact location determination devices. We have evaluated the performance of the new algorithms by comparing it against that of blind flooding as well as the fixed probabilistic approach. The results have revealed that the new algorithms exhibit superior performance in terms of both reachability and saved rebroadcast. For example, the results have shown that the new algorithms can maintain a comparable reachability level to that achieved by blinding flooding. So, without scanting reachability, the results also have revealed that adjusted probabilistic flooding can improve SRB up to 28% compared to fixed probabilistic flooding and 56% compared to blind flooding. Moreover, the new highly adjusted probabilistic flooding algorithm can improve SRB up to 47% compared to fixed probabilistic flooding and 70% compared to blind flooding, even under conditions of high node mobility and high network density without degrading reachability. It is worth noting that highly adjusted flooding manages to improve SRB by 26% over adjusted probabilistic flooding. This is because the former uses three different re-broadcasting probabilities, as opposed to two only as in the latter algorithm, depending on whether a node is located in a sparse, medium, or dense region.

In the fifth and last part of this thesis, to demonstrate the viability and effectiveness of the newly-proposed algorithms, our highly adjusted probabilistic flooding has been incorporated in the Ad hoc On-Demand Distance Vector (AODV) protocol; one of the well-known and widely studied routing algorithm over the past few years. The performance results have demonstrated that when AODV employs probabilistic-based route discovery it manages to outperform the traditional AODV that uses blind flooding-based route discovery in terms of reachability, saved rebroadcasts, as well as delay and packet delivery ratio. The new variant of AODV has been referred to as AODV-HAP for short. The other two variations of AODV are: AODV with fixed probabilistic flooding, and has been referred to as AODV-FP and the traditional AODV with blind flooding, and has been referred to as AODV-BF. The results have revealed that AODV-HAP manages to achieve a higher packet delivery ratio of data packets compared to AODV-BF and AODV-FP while keeping a lower routing overhead for different mobility scenarios. For instance, the delivery ratio in AODV-HAP is higher by up to 12% and 19% than in AODV-FP and AODV-BF when the node speed is 2 m/s and by 7% and 10% when the node speed is 12 m/s. This is achieved with a routing overhead in AODV-HAP that is lower by up to 19% and 28% than in AODV-FP and AODV-BF, respectively.

8.2 Directions for the future work

There are several interesting issues and open problems that require further investigation. These are summarised below.

- A natural continuation of research work would be to investigate the effects of other important system parameters which have not been considered in this research. For instance, the nodes' transmission range could be investigated with regard to setting the rebroadcast probability and examine through regulating the nodes' transmission radius it would be possible to maximise saved rebroadcasts whilst maintaining a low number of retransmissions. Furthermore, impact of using unidirectional as opposed to omni-directional antennas on the performance of the new adjusted and highly adjusted probabilistic flooding algorithms, could be studied.

- The performance results reported in Chapter 5 and 6 have been restricted to one hop neighbourhood information. This is mainly due to the limitation in time and computing resources available during this research. Provided adequate computing resources are made available in the future, a possible continuation of this research would be to run experiments in order to evaluate the performance merits of using two or three hop neighborhoods information for setting the re-broadcasting probability at a given node.

- A number of research studies [18, 33] have recently suggested using a counter threshold in some existing broadcasting algorithms to enable a node to keep track of the number of copies of the broadcast packets received in a given time interval. The node can then decide to re-broadcast the packet if the counter has not reached the threshold. It would be interesting to augment our algorithm with the counter-based approach and note if the resulting algorithms yield further performance improvement.

- The performance evaluation reported in Chapter 7 has been carried out in the context of the AODV routing protocol. Further research could be devoted to investigating the performance merits of the probabilistic broadcast algorithms for other well-known routing protocols such as Dynamic Source Routing (DSR) [43, 44, 54].

- The simulation experiments carried out during this research have assumed that nodes move according to the random point way model [38, 39, 51], which has been widely used in the literature [10, 13, 14, 18, 33, 50, 53, 62, 66, 92, 98, 103]. However, a number of other mobility models that have recently been suggested such as the random walk mobility model [38, 96, 97] and group mobility model [59]. A possible line of research would be to assess the performance of our proposed probabilistic flooding algorithms when these mobility models are adopted.

- Most of the research work on MANETs [1, 7, 10, 14, 17, 25, 33, 58, 63, 64], including our present study, have relied on the simulation approach (using ns-2) to evaluate their performance properties and any protocols suggested for such networks. One of the possible directions for future research would be to implement the new as well as the existing flooding algorithms on real practical MANETs in order to evaluate their performance and, more importantly, validate the results reached via the simulation approach.

- Finally, as stated above, the performance evaluation of MANETs have been conducted mostly through software simulations. In contrast, there has been relatively little activity in using analytical modelling to analyse MANETs performance. It would be interesting to develop new analytic models to investigate the interaction between the important parameters that affect the performance of probabilistic algorithms in order to gain further insight into the performance behaviour of these algorithms, especially for scenarios that are infeasible through the simulation approach, such as large network sizes and very heavy traffic loads, as they often require excessive computing times and resources to run the simulation models.

References

[1] W. Peng and X.C. Lu. On the reduction of broadcast redundancy in mobile ad hoc networks, *Proceedings of Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC' 00)*, pages 129–130, 2000.

[2] I. Stojmenovic. *Handbook of wireless networks and mobile computing*, Wiley, New York, 2002.

[3] C-K. Toh. *Ad hoc mobile wireless networks, protocols and systems*, Prentice-Hall, New York, 2002.

[4] A.D. Amis, R. Prakash, T.H.P. Vuong and D.T. Huynh. Max-min d-cluster formation in wireless ad hoc networks. *Proceedings of IEEE INFOCOM' 00*, pages 32-41, 2000.

[5] K. Fall and K. Varadhan. The ns manual, the VINT project. http://www.isi.edu/nsnam/ns/ns-man.html.

[6] M. Chatterjee, S.K. Das, and D. Turgut. WCA: A weighted clustering algorithm for mobile ad hoc networks. *Journal of Cluster Computing*, volume 5(2), pages 193–204, 2002.

[7] R. Chandra, V. Bahl, and P. Bahl. Connecting to multiple IEEE 802.11 networks using a single wireless card. *Proceedings of Twenty- Third Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2004)*, volume 2, pages 882 - 893, March 2004.

[8] K. Chen, Y. Xue, S. H. Shah, and K. Nahrstedt. Understanding bandwidth-

delay product in mobile ad hoc networks. *Computer Communications*, volume 27(10), pages 923-934, June 2004.

[9] Z. Tang and J. J. Garcia-Aceves, Collision-avoidance transmission scheduling for ad-hoc networks. *Proceedings IEEE Conf. Communications*, volume 3, pages 1788 -1794, 2000.

[10] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu. The broadcast storm problem in a mobile ad hoc network, *Wireless Networks*, volume 8 (2), pages 153-167, 2002.

[11] C. R. Lin, M. Gerla. Adaptive clustering for mobile wireless networks, *IEEE Journal of Selected Areas in Communications*, volume 15(7), pages 1265-1275, 1997.

[12] R. Sivakumar, P. Sinha and V. Bharghavan. CEDAR: A core extension distributed ad hoc routing algorithm. *IEEE Journal of Selected Areas in Communications* volume 17(8), pages 1454-1465, 1999.

[13] A. B. McDonald and T. F. Znati. A mobility based framework for adaptive clustering in wireless ad hoc networks. *IEEE Journal of Selected Areas in Communications*, volume 17(8), pages 1466-1487, 1999.

[14] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen and J.-P. Sheu. The broadcast storm problem in a mobile ad hoc network. *Proceedings Of ACM/IEEE Mobicom'99*, pages 151-162, August 1999.

[15] A. Amis and R. Prakash. Load-balancing clusters in wireless ad hoc networks. *Proceedings ASSET' 2000*, pages 25-32, 2000.

[16] S. Guha and S. Khuller. Approximation algorithms for connected dominating

sets. *Algorithmica*, volume 20(4), pages 374 -387, 1998.

[17] B. Williams and T. Camp. Comparison of broadcasting techniques for mobile ad hoc networks. *Proceedings ACM Symposium Mobile Ad Hoc Networking & Computing (MOBIHOC'* 02), pages 194–205, 2002.

[18] Y.-C. Tseng, S.-Y. Ni, and En-YU Shih. Adaptive approaches to relieving broadcast storm in a wireless multihop mobile ad hoc network. *IEEE Transactions on Computers*, volume 52(5), pages 545-557, May 2003.

[19] J. Wu and W. Lou. Forward-node-set-based broadcast in clustered mobile ad hoc networks, special issue on Algorithmic, Geometric, Graph, Combinatorial, and Vectors. *Wireless Networks and Mobile Computing*, volume 3(2), pages 155-173, 2003.

[20] Y. Sasson, D. Cavin, A. Schiper. Probabilistic broadcast for flooding in wireless mobile ad hoc networks, *Swiss Federal Institute of Technology* Technical report IC/2002/54, 2002.

[21] A. Qayyum, L. Viennot and A. Laouiti. Multipoint relaying for flooding broadcast in mobile wireless networks. *Proceedings of Hawaii International Conference on System Sciences*, pages 3898-3907, January 2002.

[22] W. Lou and J. Wu. On reducing broadcast redundancy in mobile ad hoc Networks. *IEEE Transactions Mobile Computing*, volume 1(2), pages 111-123, 2002.

[23] H. Dubois-Ferriere, Age Matters, Efficient route discovery in mobile ad hoc Networks Using Encounter Ages, *Proceedings MobiHoc 2003*, pages 257-266, June 2003.

[24] J. Lipman, P. Boustead and J. Judge. Efficient and scalable information dissemination in mobile ad hoc networks. *Proceedings of Ad-hoc Networks and Wireless (ADHOC-NOW' 02)*, pages 119-134, 2002.

[25] J. Cartigny and D. Simplot. Border node retransmission based probabilistic broadcast protocols in ad-hoc networks, *Telecommunication Systems*, volume 22 (4), pages 189–204, 2003.

[26] J. Cartigny, D. Simplot, and I. Stojmenovic. Localized minimum-energy broadcasting in ad-hoc networks. *Proceedings of Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003)*, volume 3, pages 2210-2217, March 2003.

[27] J. Wu and F. Dai. Broadcasting in ad hoc networks based on self-Pruning. *Proceedings of Annual Joint Conference IEEE Computer and Communications Societies (INFOCOM' 03)*, volume 3, pages 2240-2250, 2003.

[28] C. Ho, K. Obraczka, G. Tsudik, and K. Viswanath. Flooding for reliable multicast in multi-hop ad hoc networks. *Proceedings of International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communication (DIALM' 99)*, pages 64-71, 1999.

[29] S. R. Das, R. Castaneda, J. Yan, and R. Sengupta. Comparative performance evaluation of routing protocols for mobile, ad hoc networks, *Proceedings of seventh International Conference on Computer Communications and Networks (IC3N '98)*, pages 153–161, October 1998.

[30] W. Lou and J. Wu. A cluster-based backbone infrastructure for broadcasting in MANETs. *Workshop on Wireless, Mobile, and Ad Hoc Networks*

(WMAN'2003), IPDPS 2003 Workshops, pages 221-225, 2003.

[31] W. Lou and J. Wu, Localized broadcasting in mobile ad hoc networks using neighbor designation, *Mobile Computing Handbook*, M. Ilyas and I. Maghoub, CRC Press, pages 663-688, 2004.

[32] P.-K. Hung, J.-P. Sheu, and C.-S. Hsu, Scheduling of broadcasts in multihop wireless networks, *Proceeding of the International Conference on European Wireless 2002*, pages 163-169, 2002.

[33] Q. Zhang and D.P. Agrawal. Dynamic probabilistic broadcasting in MANETs, *Journal of Parallel Distributed Computing*, volume 65(2), pages 220-233, May 2005.

[34] M. R. Pearlman and Z. J. Haas. Determining the optimal configuration of the zone routing protocol. *IEEE Journal on Selected Areas in Communications*, volume 17(8), pages 1395–1414, 1999.

[35] V. Park and S. Corson, Temporally ordered routing algorithm (TORA), Internet draft, March 2004. http://www.ietf.org/proceedings/02mar/I-D/draft-ietf-manet-tora-spec-04.txt.

[36] C. Perkins and E. M. Royer, Ad-hoc on-demand distance vector routing. *Proceedings of 2nd IEEE Workshop on Mobile Computing Systems and Applications (WMCSA'99)*, pages 90–100, 1999.

[37] B. P. Crow, I. Widjaja, L.G, Kim and P.T. Sakai, IEEE 802.11 Wireless local area networks. *IEEE Communications Magazine*, volume 35(9), pages 116-126, September 1997.

[38] T. Camp, J. Boleng and V. Davies. A Survey of mobility models for ad hoc

network research. *Wireless Communication & Mobile Computing, Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, volume 2(5), pages 483-502, 2002.

[39] W. Navidi and T. Camp. Stationary distributions for the random waypoint mobility model. *IEEE Transactions on Mobile Computing*, volume 3(1), pages 99-108, 2004.

[40] Y.-C. Tseng, S.-Y. Ni, and E.-Y. Shih. Adaptive Approaches to Relieving Broadcast Storms in a wireless multihop mobile ad hoc network. *ICDCS '01, Proceedings of the 21st International Conference on Distributed Computing Systems*, pages 481-488, 2001.

[41] T. Clausen and P. Jacquet. Optimized link state routing protocol (OLSR). http://www.ietf.org/rfc/rfc3626.txt, October 2003.

[42] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark. Scenario based performance analysis of routing protocols for mobile ad-hoc networks. *Proceedings of the fifth annual ACM/IEEE international conference on Mobile computing and networking*, pages 195-206, 1999.

[43] D. B. Johnson and D. A. Maltz. *Dynamic source routing in ad hoc wireless Network*. Kluwer Academic Publishers, 1996.

[44] D. B. Johnson, D. A. Maltz, and Y.-C. Hu. The dynamic source routing protocol for mobile ad hoc networks (DSR). Internet Draft, draft-ietf-manet-dsr-10.txt, July 2004.

[45] G. Lin, G. Noubir, and R. Rajamaran. Mobility models for ad hoc network simulation. *Proceedings of Twenty-Third Conference of the IEEE*

Communications Society (INFOCOM 2003), volume 1, pages 45-463, March 2004.

[46] B.-J. Kwak On the scalability of ad hoc networks. *IEEE Communications Letters*, volume 8, pages 503-505, August 2004.

[47] R. B. S. Konduru. An adaptive distance vector routing algorithm for mobile, ad hoc networks. *Proceedings of Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2001)*, volume 3, pages 1753-1762, April 2001.

[48] C. K. Toh. Maximum battery life routing to support ubiquitous mobile computing wireless ad hoc networks. *IEEE Communications Magazine*, volume 39(6), pages 138 -147, June 2001.

[49] H. Lim, K. Xu, and M. Gerla. TCP performance over multipath routing in mobile ad hoc networks. *Proceedings of the 38th annual IEEE International Conference on Communications ICC 2003*, pages 1064-1068, May 2003.

[50] S. Kurkowski, T. Camp, and M. Colagrosso. MANET simulation studies. ACM *SIGMOBILE Mobile Computing and Communication Review*, volume 9(4), pages 50-61, 2005.

[51] Mobile ad hoc Networking (MANET), Routing protocol performance issues and evaluation considerations. *IETF RFC 2501*, January 1999.

[52] T. W. Mehran Abolhasan and E. Dutkiewicz. A review of routing protocols for mobile ad hoc networks. *Ad Hoc Networks*, volume 2(1), pages 1-22, January 2004.

[53] J. Yoon, M. Liu, and B. Noble. Random waypoint considered harmful.

Proceedings of Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003), volume 2, pages 1312-1321, March 2003.

[54] E. Nordstrom. DSR-UU: A Dynamic source routing protocol implementation. http://core.it.uu.se/core/index.php/DSR-UU, 2004.

[55] C. E. Perkins. *Ad Hoc Networking*. Addison Wesley Professional, 2001.

[56] C. E. Perkins, E. M. Belding-Royer, and S. R. Das. *Ad hoc on-demand distance vector (AODV) routing*. request for comments, http://www.ietf.org/rfc/rfc3561.txt, July 2003. Experimental RFC.

[57] C. E. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. *Proceedings of the conference on Communications architectures, protocols and applications*, pages 234-244, 1994.

[58] P. D. Welch. The statistical analysis of simulation results. In S. Lavenberg, editor, *The Computer Performance Modeling Handbook*, pages 268-328. Academic Press, 1983.

[59] X. Hong. A Group mobility model for ad hoc wireless networks. *Proceedings of MSWiM/99*, pages 53-60, 1999.

[60] H. Lundgren, E. Nordstrom, and C. Tschudin. Coping with communication gray zones in IEEE 802.11b based ad hoc networks. *WOWMOM'02: Proceedings of the 5th ACM international workshop on Wireless mobile multimedia*, pages 49-55, 2002.

[61] Julien Cartigny, François Ingelrest, David Simplot-Ryl, Ivan Stojmenovic,

Localized LMST and RNG based minimum-energy broadcast protocols in ad hoc networks. *Ad Hoc Networks*, volume 3(1), pages 1-16, 2005.

[62] G. Anastasi, E. Borgia, M. Conti, and E. Grego. IEEE 802.11 Ad hoc networks: Performance measurements. *Proceedings of the 23rd International Conference on Distributed Computing Systems Workshops (ICDCSW'03)*, pages 758-763, May 2003.

[63] F. Garcia, J. Solano and I. Stojmenovic, Connectivity based k-hop clustering in wireless networks, *Telecommunication Systems*, volume 22(4), pages 205-220, 2003.

[64] H. Y. Huang, A. Khendry and T.G. Robertazzi, A self-organizing protocol for small ad hoc networks, *IEEE Trans. on Aerospace and Electronic Systems*, volume 38(2), pages 378-387, April 2002.

[65] S. R. Das, C. E. Perkins, and E. Royer. Performance comparison of two on-demand routing protocols for ad hoc networks, *Proceedings of 19th Annual of IEEE Computer and Communications Societies (INFOCOM'2000)*, pages 3-12, March 2000.

[66] B. Yassein, M. Ould-Khaoua, and S. M. Papanastasiou. On the performance of probabilistic flooding in mobile ad hoc networks, *Proceedings of 1st International Workshop on Performance Modeling in Wired, Wireless, Mobile Networking and Computing (PMW2MNC' 05), held in conjunction with ICPADS'2005*, pages 125-129, July 2005.

[67] S. Xu and T. Saadawi. Revealing the problems with 802.11 medium access control protocol in multi-hop wireless ad hoc networks. *Computer Networks*,

volume 38(4), pages 531-548, March 2002.

[68] J. Kong. Providing robust and ubiquitous security support for mobile ad-hoc networks. *Proceedings of 2001 Int'l Conf. Network Protocols*, pages 251-260, 2001.

[69] Mobile metropolitan ad hoc network (MobileMAN), IST-2001-18113 Project, funded by the EC FET-IST, http://cnd.iit.cnr.it/mobileMAN/

[70] F. Delmastro, From pastry to CrossROAD: Cross-layer RNG overlay for ad hoc networks, *Proceedings of Workshop of Mobile Peer-to-Peer 2005, in conjunction with the PerCom 2005 conference*, Kauai Island, Hawaii, March 2005.

[71] S. Ramanathan and M. Steenstrup A survey of routing techniques for mobile communications networks, *Mobile Networks and Applications*, volume 1(2), pages 89-104, 1996.

[72] V. Rodoplu and T. Meng. Minimum energy mobile wireless networks. *IEEE Journal of Selected Areas in Communications*, volume 17(8), pages 1333-1344, 1999.

[73] J. Cartigny, F. Ingelrest, and D. Simplot. RNG relay subset flooding protocols in mobile ad-hoc networks. *International Journal of Foundations of Computer Science*, volume 14(2), pages 253–265, 2003.

[74] Ian D. Chakeres and Elizabeth M. Belding-Royer. The utility of hello Messages for determining link connectivity. *Proceedings of the 5th International Symposium on Wireless Personal Multimedia Communications (WPMC) 2002, Honolulu, Hawaii*, pages 32-41, October 2002.

[75] I. Stojmenovic, S. Seddigh, and J. Zunic. Dominating sets and neighbor elimination based broadcasting algorithms in wireless networks. *IEEE Trans. on Parallel and Distributed Systems*, volume 13(1), pages 14–25, January 2002.

[76] E. M. Royer and C. K. Toh. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications*, volume 6(2), pages 46–55, 1999.

[77] W. Peng and X. Lu. AHBP, An efficient broadcast protocol for mobile and hoc networks. *Journal of Computer Science and Technology*, volume 16(2), pages 114–125, March 2001.

[78] J. Boleng. Normalizing mobility characteristics and enabling adaptive protocols for ad hoc networks. *Proceedings of the IEEE Local and Metropolitan Area Networks Workshop (LANMAN)*, pages 9–12, 2001.

[79] M. Takai, J. Martin, and R. Bagrodia. Effects of wireless physical layer modeling in mobile ad hoc networks. *MobiHoc '01, Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing*, pages 87-94, 2001.

[80] R. Van Nee, G. Awater, M. Morikura, H. Takanashi, M. Webster and K.W. Halford, New high-rate wireless LAN standards. *IEEE Communications Magazine*, volume 37(12), pages 82-88, December 1999.

[81] IEEE 802.11 Working Group Task Group for WLAN. IEEE 802.11 WirelessLocal Area Networks (WLAN). http://ieee802.org/11/

[82] F. Dai and J. Wu. Distributed dominant pruning in ad hoc wireless networks. *Proceedings of IEEE 2003 International Conference on Communications (ICC*

2003), volume 1, pages 353–357, May 2003.

[83] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. Span: An energy efficient coordination algorithm for topology maintenance in ad hoc wireless networks. *ACM Wireless Networks Journal*, volume 8(5), pages 481–494, September 2002.

[84] K. M. Alzoubi, P. J. Wan, and O. Frieder. Message-optimal connected dominating sets in mobile ad hoc networks. *Proceedings of 3rd ACM Int'l Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC'2002)*, pages 157–164, 2002.

[85] H. Lim and C. Kim. Flooding in wireless ad hoc networks. *Computer Communications Journal*, volume 24(4), pages 353–363, 2001.

[86] K. Xu, M. Gerla, and S. Bae. How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks. *Global Telecommunications Conference, 2002. GLOBECOM '02*, volume 1, pages 72-76, November 2002.

[87] Q. Li, J. Aslam, and D. Rus. Online power-aware routing in wireless Ad-hoc networks. *Proceedings of the 7th annual international conference on Mobile computing and* networking, pages 97-107, 2001.

[88] F. Dai and J. Wu, Performance analysis of broadcast protocols in ad hoc networks based on self-pruning, *IEEE Transactions on Parallel and Distributed Systems*, volume 15(11), pages 1027-1040, November 2004

[89] F. Dai and J. Wu, An Extended localized algorithm for connected dominating set formation in ad hoc wireless networks, *IEEE Transactions on Parallel and Distributed Systems*, volume 15(10), pages 908-920, October 2004.

[90] J. Wu, W. Lou, and F. Dai, Extended multipoint relays to determine connected dominating sets in MANETs, *IEEE Transactions on Computers*, volume 55(3), pages 334-347, March 2006.

[91] F. Dai and J. Wu, Efficient broadcasting in ad hoc networks using directional antennas, *IEEE Transactions on Parallel and Distributed Systems*, volume 17(4), pages 335-347, April 2006.

[92] M. Cardei, J. Wu, and S. Yang, Topology control in ad hoc wireless networks using cooperative communication, *IEEE Transactions on Mobile Computing*, volume 5(6), pages 711-724, June 2006.

[93] J. Wu and F. Dai, Mobility-sensitive topology control in mobile ad hoc networks, *IEEE Transactions on Parallel and Distributed Systems*, volume 17(6), pages 522-535. June 2006.

[94] J. Wu, M. Cardei, F. Dai, and S. Yang, Extended dominating set and its applications in ad hoc networks using cooperative communication, *IEEE Transactions on Parallel and Distributed Systems*, volume 17(8), pages 851-864, August 2006.

[95] F. Ingelrest, D. Simplot-Ryl, I. Stojmenovic, Optimal transmission radius for energy efficient broadcasting protocol in ad hoc and sensor networks; *IEEE Transactions on Parallel and Distributed Systems*, volume 17(6), pages 536 – 547, June 2006.

[96] I. F. Akyilidz, Y.-B. Ln, W.-R. Lai, R.-J. Chen. A new random walk model for PCS networks, *IEEE Journal on Selected Area in Communications*, volume18 (7), pages 1254-1259, July 2000.

[97] B. Jabbari, Y. Zhou, F. Hellier, Random walk modeling of mobility in wireless networks, *Proceedings of IEEE VTC'98*, pages 639-643, May 1998.

[98] P. Santi and D. M. Blough. The critical transmitting range for connectivity in sparse wireless ad hoc networks. *IEEE Trans. on Mobile Computing*, volume 2(1), pages 25-39, March 2003.

[99] F. Xue and P. R. Kumar. The number of neighbors needed for connectivity of wireless networks. *ACM Journal of Wireless Networks*, volume 10(2), pages 169-181, March 2004.

[100] D. Niculescu and B. Nath, Ad hoc positioning system (APS), *Proceedings of IEEE Globecom 2001*, pages 2926-2931, 2001.

[101] C. Bettstetter and C. Hartmann. Connectivity of wireless multihop networks in a Shadow Fading Environment. *ACM/Springer Wireless Networks*, volume 11(5), pages 571-579, September 2005.

[102] S. Xu and T. Saadawi. Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks. *IEEE Communications Magazine*, volume 39(6), pages 130-137, June 2001

[103] R. Sollacher, M. Greiner, and I. Glauche. Impact of interference on the wireless ad-hoc networks capacity and topology. *Wireless Networks*, volume 12(1), pages 53-61, 2006.

[104] M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie and S. Papanastasiou, Performance analysis of adjusted probabilistic broadcasting in mobile ad hoc networks, *International Journal of Wireless Information Networks. Elsevier*, volume 13(2), pages 1-14, Springer Netherlands, Mar 2006

[105] M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie and S. Papanastasiou, The highly adjusted probabilistic broadcasting in mobile ad hoc networks, *Proceedings of the 6th Annual PostGraduate Symposium on the Convergence of Telecommunications, Networking & Broadcasting, (PGNET 2005)*, Liverpool John Moores University, UK, pages 135-140, June 2005.

[106] Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie, S. Papanastasiou and A. Jamal, improving route discovery in on-demand routing protocols using local topology information in MANETs, *Proceedings of the Ninth ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM 06)*, pages 95-99 October 2006.

Publications during the course of this research

* M. Bani-Yassein, M. Ould-Khaoua and L. M. Mackenzie route discovery of adjusted probabilistic flooding in MANETs, *Telecommunication Systems.* under review, 2007.
* M. Bani-Yassein, M. Ould-Khaoua and L. M. Mackenzie, applications of probabilistic flooding in MANETs, Accepted to appear in *International Journal of Computers and Applications, (ACTA)*, 2007.
* M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie and S. Papanastasiou, Performance analysis of adjusted probabilistic broadcasting in mobile ad hoc networks, *International Journal of Wireless Information Networks. Elsevier,* volume 13(2), pages 1-14, Springer Netherlands, Mar 2006.
* M. Bani-Yassein, M. Ould-Khaoua, L.M. Mackenzie, and S. Papanastasiou, Applications of performance evaluation of adjusted probabilistic broadcasting in MANETs, *The 2nd IEEE International Symposium on Dependable, Autonomic and Secure Computing (DASC'06),* Indiana University, Purdue University, Indianapolis, USA, pages 245-249, October 2006.
* M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie, S. Papanastasiou and A. Jamal, Improving route discovery in on-demand routing protocols using local topology information in MANETs, *Proceedings of the Ninth ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM 06),* pages 95-99, October 2006.

* J. Abdulai, M. Ould-Khaoua, L.M. Mackenzie and M. Bani-Yassein, Efficient forwarding probability for on-demand probabilistic route discovery in MANETs, *Proceedings of 22nd UK Performance Engineering Workshop (UKPEW 2006)* pages 9-15, July 2006.
* J. Abdulai, M. Ould-Khaoua, L.M. Mackenzie and M. Bani-Yassein, On the forwarding probability for on-demand probabilistic route discovery in MANETs, *Proceedings of 7th Annual PostGraduate Symposium on The Convergence of Telecommunications, Networking and Broadcasting (PGNet 2006)*, pages 120 – 125, June 2006.
* M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie and S. Papanastasiou, The highly adjusted probabilistic broadcasting in mobile ad hoc networks, *Proceedings of the 6th Annual PostGraduate Symposium on the Convergence of Telecommunications, Networking & Broadcasting, (PGNET 2005)*, Liverpool John Moores University, UK, pages 135-140, June 2005.
* M. Bani-Yassein, M. Ould-Khaoua, S. Papanastasiou, Performance analysis of adjusted probabilistic broadcasting in MANETs, *Technical Report*, TR-2005-195, Department of Computing Science, University of Glasgow, April 2005.
* M. Bani-Yassein, M. Ould-Khaoua, L. M. Mackenzie, S. Papanastasiou, Improving the performance of probabilistic flooding in MANETs, *Proceedings of International Workshop on Wireless Ad-hoc Networks (IWWAN-2005)*, Waterloo campus of King's College, London, United Kingdom, pages 62-68, May 2005.
* M. Bani-Yassein, M. Ould-Khaoua, S. Papanastasiou, On the performance of probabilistic flooding in mobile ad hoc networks, *Proceedings of International*

Workshop on Performance Modelling in Wired, Wireless, Mobile Networking and Computing in conjunction with 11th International Conference on Parallel and Distributed Systems (ICPADS' 05), IEEE Computer Society Press, pages 125-129, July 2005.

* M. Bani-Yassein, M. Ould-Khaoua, S. Papanastasiou, Performance evaluation of flooding in MANETs in the presence of multi-broadcast traffic, *Proceedings of International Workshop on Performance Modeling and Analysis of Communication in Parallel, Distributed, and Grid Networks (PMAC-PDG' 05), To be held in conjunction with 11th International Conference on Parallel and Distributed Systems (ICPADS' 05)*, IEEE Computer Society Press, pages 505-509, July 2005.
* M. Bani-Yassein, M. Ould-Khaoua, S. Papanastasiou, A. Al-Ayyoub, On the effect of mobility and density on probabilistic flooding in MANETs, *Proceedings of INT. Working Conference on Performance Modeling and Evaluation of Heterogeneous Networks (HET-NETs '04)*, British Computer Society (BCS), IEE, Ilkley, West Yorkshire, U.K, pages 63/1-63/9, July 2004.
* M. Bani-Yassein, M. Ould-Khaoua S. Papanastasiou, A. Al-Ayyoub, Analysis of density effect in probabilistic flooding in MANETs, *Proceedings of* 5^{th} *International Conference on Information Technology* (*ACIT' 04*), Constantine, Algeria, vol. 1, pages 108-117, December 2004.
* M. Bani-Yassein, M. Ould-Khaoua S. Papanastasiou, A. Al-Ayyoub, density effect in probabilistic flooding in MANETs, *Technical Report, TR-2004-168*, Department of Computing Science, University of Glasgow, 2004.
* M. Bani-Yassein, S. Papanastasiou, M. Ould-Khaoua, Performance Analysis of

probabilistic flooding in MANETs, *Proceedings of 20th annual UK Performance Engineering Workshop (UKPEW '04)*. University of Bradford, pages 200-209, July, 2004.

* M. Bani-Yassein, S. Papanastasiou, M. Ould-Khaoua, A Simulation study of performance probabilistic flooding in MANETs, *Technical Report*, TR-2004-167, Department of Computing Science, University of Glasgow, 2004.

GLASGOW UNIVERSITY LIBRARY